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Cost-effectiveness of Climbing Lanes: Safety, Level of Service and Cost Factors

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Abstract: The objectives of this study were: (a) to develop a methodology for assessing the cost-effectiveness of climbing lanes on two-lane highways, based on level of service improvement, reduction of delay, increased safety, and cost of providing a climbing lane; (b) to develop a practical , user-friendly microcomputer-based tool to evaluate the cost-effectiveness of proposed climbing lanes.

The speed-distance functions, developed in a previous study sponsored by the Ministry of Transportation, Ontario, were incorporated in a technique for the definition of climbing lane options in terms of location and length of such lanes. Methodology was developed for estimating the level of service and safety improvements that are obtainable from climbing lanes. The results of functions developed for the estimation of level of service factors (ie., platooning, average speed) were consistent with field data.

A methodology was defined for the study of cost-effectiveness of climbing lanes and was implemented in the form of a user-friendly microcomputer program. The use of cost-effectiveness methodology and the microcomputer program is illustrated in the form of a case study.

Comments: Final report of Research and Development Project 25193. User's manual (TDS-90-09) and Programmer's manual (TDS-90-10) for CECL computer program also available.

Key Words: climbing lanes, two-lane road, highway, cost, level of service, model, cost-effectiveness, safety, truck, heavy vehicle

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EXECUTIVE SUMMARY

Climbing lanes, although costly, are used as a means for overcoming the operational and safety problems attributed to trucks and other slow moving vehicles on upgrade sections of two lane highways. Due to gradeability limitation of heavy vehicles, a substantial drop in the speed of heavy vehicles results in:

. restricted opportunities for overtaking slow vehicles,
. increased platooning,
. reduced average speed, and
. increased safety hazard.

The provision of climbing lanes on upgrade sections and passing lanes elsewhere on two lane highways, in addition to the immediate improvement of level of service and safety, would also be a step towards the ultimate development of a four lane cross section. However, methodological deficiencies have not permitted analysis of the operational, safety and ultimately cost-effectiveness of climbing lanes.

One methodological deficiency, namely a reliable means to predict the speed-distance profile of heavy vehicles, has already been addressed through a previous project funded by the MTO, entitled "Review of MTO Truck Climbing Lane Criteria". Speed-distance curves were developed and were verified with field data. The speed-distance curves are intended for use by designers in the identification of the critical length of grade for given highway and traffic characteristics. Indirectly, such information is useful for the estimation of the service level offered to traffic on grade.

This study was initiated to overcome other methodological deficiencies. Specifically, this study has:

. incorporated the speed-distance functions, developed in the previous study, in a technique for the identification of sites for the provision of climbing lanes and the definition of length and location of climbing lanes,

. developed methodology for estimating the level of service and safety improvements that are obtainable from climbing lanes on two lane highway upgrade sections,

. developed methodology for the study of cost-effectiveness of climbing lanes, and

. operationalized the above methodologies in the form of a user-friendly microcomputer program for the expedient development of climbing lane options and their cost-effectiveness evaluation.

Two approaches were defined for making the effective use of speed-distance functions. In one case, the concept of the critical length of grade was formalized by adopting the criterion of a drop in speed of the design truck to the extent of 15 km/h (or higher) as compared to approach speed for the identification of a candidate site for a climbing lane. The starting point for the climbing lane is specified as that location where the speed of truck drops by 15 km /h and the ending point corresponds to the location where the truck's speed rises back to a level so that the speed difference is not higher than 15 km/h. In association with a tabular version of speed-distance functions, this criterion was implemented within a microcomputer program.

The second approach offers the opportunity to start and end a climbing lane at user-specified locations. Such a flexibility recognizes that due to topographic, geometric design and cost constraints, a designer may wish to deviate from the above noted formal criterion.

Recognizing the widespread use of the Highway Capacity Manual (1985), it was believed to be appropriate to adopt its procedures and guidelines for the analysis of approach and upgrade sections without climbing lanes. However, due to the absence of guidelines and procedures for the estimation of level of service of two lane highway upgrade sections containing climbing lanes, new techniques had to be developed. In the absence of data on traffic and geometric design characteristics of a large number of sites "without climbing lane" and "with climbing lane", such data were generated through a specially designed procedure based on the random selection of such characteristics.

The next step required the use of a microscopic simulation model to study the performance of such upgrade sites. Two such models of comparable features, namely TWOPAS and TRRAR were evaluated in terms of their data requirements and outputs. The development of the TWOPAS model was sponsored by the Federal Highway Administration (FHWA), U.S.A. and the TRRAR model was developed by the Australian Road Research Board. The TWOPAS model was selected on the basis of model capabilities and familiarity with the program outputs.

Traffic and geometric design data in association with outputs of the TWOPAS model were used to investigate level of service indicators such as "percent of vehicles in platoons", "spot speed" and "average speed". Although it was recognized that

"percent vehicles in platoons" is an important indicator of level of service, it could not be used directly to quantify delay reduction due to climbing lanes. Consequently, the average speed was used for this purpose.

Regression equations (macrosimulation models) were developed for average speed and percent of vehicles in platoons. However, the average speed equations were the ones to be used for the estimation of reduction in delay.

The models were validated through a comparison of their outputs with field data obtained from selected sites. Field studies measured speed through radar meters and video tapes were used to obtain data on platooning, average speed, traffic volume and composition. Estimates of average speed for both sites compare favourably with field data.

Percent vehicles in platoons estimated by TWOPAS model as well as regression equations match closely with field data for the site with a climbing lane. For the second site, the models appear to under estimate platooning. However, the presence of an exit upstream may have caused a higher than normal extent of platooning. Considering that the methodology developed here uses the average speed models, the validation process is considered satisfactory.

The methodology developed for the estimation of upgrade average speed for sections with climbing lanes supplements the HCM (1985) procedures. From the regression equations, an increase in average upgrade speed attributable to a climbing lane is estimated and added to the speed obtained from HCM (1985) procedures. A number of checks are made to avoid inconsistencies between approach and upgrade speeds and the adjusted speed is adopted for the assessment of level of service and calculation of delay reduction. This methodology overcomes the deficiencies of the HCM (1985) procedures and also reconciles results for the approach and upgrade sections.

This study required functions to quantify accident involvement rates for upgrade sections of two lane highways. Two regression equations were developed based on information reported in the literature. The first equation can be used to estimate accident involvement rate as a function of drop in speed upgrade as compared to the approach speed, provided that such speed drop is from 0 to 15 km/h. The second equation is intended for speed reductions of more than 15 km/h.

The cost-effectiveness methodology offers various options for the evaluation of climbing lane options. Also, sensitivity tests could be carried out for one site by varying traffic volume and other factors. Effectiveness measures could be studied

individually (against cost) or an overall measure of effectiveness could be developed, based on multiple measures (e.g., delay reduction, safety improvement) and viewed against cost. The methodology also permits the study of economic feasibility. Such a study would of course require the quantification of benefits.

The above described methodological framework and constituent techniques are implemented in the form of a microcomputer program. The program has been carefully designed to be user friendly and offers much flexibility to the user to apply various modules (A to G). Major components of the program include: input (site and traffic characteristics), development of climbing lane alternatives, performance characteristics and checking warrants for the provision of climbing lanes, and cost-effectiveness studies.

A example of the use of microcomputer program is provided in the report. A comparison is made between manual computation and computer outputs. The example serves the purposes of checking the logic and computational routines of the programme and also it illustrates the use of methodology for studying the cost-effectiveness of climbing lanes.

A number of conclusions and recommendations are contained in the report. Highlights are provided here. It became clear during the course of this study that the level of service criteria and estimation methods contained in Chapter 8 of the Highway capacity Manual (1985) applicable to upgrade sections have not been harmonized with those intended for approaches to the upgrade sections. The methodology developed here supplements the HCM (1985) procedures and also overcomes its deficiencies for the analysis of the operational effectiveness of two lane highway sections containing climbing lanes.

The methodology developed, verified against field data, and implemented as a "user friendly" microcomputer program, incorporates all determinants of the cost-effectiveness of climbing lanes. The level of indicators are related to such variables as grade, length of grade, two-way traffic volume, directional split of traffic, percent trucks, percent recreational vehicles, and controls on overtaking.

The overall methodology enables cost-effectiveness and economic feasibility type of evaluations of passing lane projects. Results obtained from example application applications appear to be logical and reasonable. The modular nature of the microcomputer program enables expedient and comprehensive analysis and evaluation of climbing lane options. The methodology developed and the microcomputer program are recommended for practical use by the Ministry of Transportation, Ontario.

Future improvements to the models would enhance the utility of the methodology and are, therefore, recommended. Finally, it is recommended that the methodology developed in this study be extended for the priority analysis of passing lane/climbing solutions on two lane rural roads.

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The opinions expressed are those of the authors. They do not necessarily reflect the views of MTO or of Carleton University.

Chapter 1

INTRODUCTION

1.1 Background

On upgrade sections of two lane highways, trucks and slow moving recreational vehicles experience a reduction in their speed. A substantial drop in the speed of trucks and other slow moving vehicles cause platoons, reduces service flow rates, and restricts opportunities to safely pass slow moving vehicles. Climbing lanes provide relief from slow moving vehicle-induced platoons on grade and improve safety. The provision of climbing lanes in association with passing lanes on two lane highways is also a step towards the ultimate twinning of highways into a four lane cross section.

Climbing lanes have been built in almost all jurisdictions in Canada and the U.S.A. Other countries around the world (e.g., Australia, Sweden, U.K.) have also installed climbing lanes. While a variety of warrants have been used for the provision of climbing lanes, the underlying considerations, although exercised informally, have centred on operations, safety and economics.

Truck speed-distance functions, although highly dated, have enabled the transportation planners and designers to establish the effect of given upgrade sections on truck speed. Methodology has been available for analyzing the operations of upgrade sections of two lane highways without climbing lanes. However, practical methods for the study of operational effectiveness of upgrade sections with climbing lanes have not been developed. The safety of climbing lane sites has been related, although in an informal fashion, to a drop in speed of heavy vehicles on upgrade sections. Due to the absence of methodology, an improvement in speed caused by climbing lanes and its effect on safety could not be quantified.

While the importance of the cost-effectiveness of climbing lanes, combining the operational, safety and cost factors, has been recognized, methodological deficiencies have prevented such analyses from being performed. Given the high cost of climbing lanes (i.e., typically between one-half to one million dollars), it is essential that design and investment decisions are based on realistic truck and other traffic performance information as well as methodology for assessing the cost-effectiveness of design and investment options.

In a previous project funded by the Ministry of Transportation, Ontario (MTO), speed-distance curves were

developed using two independent methods and were verified against field data. Also, warrants for the provision of climbing lanes were studied [1]. The speed-distance curves enable the designer to check the drop in speed of heavy vehicles and to identify sites that would become candidates for climbing lanes. Also, these curves could be used for establishing the starting point and length of climbing lanes.

Effective use of speed-distance curves in design and investment decisions requires methodology for analyzing climbing lane sites. For climbing lane alternatives, the designer has to check on operational improvements that can be expected from climbing lanes (i.e., level of service improvement -- based on a variety of indicators such as a drop in the percent of vehicles in platoons and average speed improvement). A methodology is suggested by the Highway Capacity Manual (HCM, 1985) for analyzing the performance of upgrade sections of two lane roads without climbing lanes [2]. However, methodology for estimating the level of service of an upgrade section containing a climbing lane is not available.

In addition to analyzing the level of service improvements obtainable from climbing lanes, it would be desirable to check on the feasibility and cost-effectiveness of climbing lane alternatives. This process requires the knowledge and judgement of experienced designers and planners as well as methodological advances. Also, a large number of repetitive calculations would be required for testing sensitivity of answers to changes in inputs.

A "user friendly" objective tool is required that may be used throughout Ontario in order to check on the satisfaction of truck speed and level of service type of warrants for climbing lanes, and to assess their cost-effectiveness. Such a methodology could potentially support the study of cost-effectiveness of truck climbing lanes as safety and level of service improvement measures.

1.2 Research Objectives and Scope

The objectives of this research are:

1. to develop a methodology for studying the cost-effectiveness of climbing lanes, and

2. to develop a practical, user-friendly microcomputer-based tool to evaluate the cost-effectiveness of proposed climbing lane solutions on two lane highways, including such factors as travel time savings and increased safety.

As for scope, this study has focussed on the climbing lane aspect of the overall capacity and level of service of two lane highways. In the design of this study, the interrelationships between truck climbing performance and overall traffic stream characteristics have been incorporated. However, it was not the intent of this research to investigate the overall performance of two lane roads.

Although safety, as an effectiveness measure was included in the cost-effectiveness methodology, the state of knowledge (i.e., availability of safety data) did not permit its treatment to the same degree of detail as level of service.

1.3 Report Organization

Following this introductory chapter, the overall research framework is described in Chapter 2. The requirements for the development of methodology, the research approach and the cost-effectiveness model structure are described. Chapter 3 covers methodological considerations in defining climbing lane options. The theoretical as well as practical viewpoints are noted.

Techniques for the estimation of level of service and delay are discussed in Chapter 4. The adoption of HCM (1985) procedures for the analysis of approach and upgrade sections without an auxiliary lane is discussed and deficiencies are noted. New methodology for the analysis of upgrade sections with a climbing lane is reported as well in Chapter 4.

Chapter 5 is devoted to the subject of safety of two lane highway sections on grade, with and without climbing lanes. The development of a method to quantify safety impacts is described.

Chapter 6 reports the process of verification of models used for the estimation of operational performance of two lane highways with and without climbing lanes. The process and results of checks made on the output of models against field data are described.

Chapter 7 describes the theoretical aspects of the cost-effectiveness methodology for assessing the merits of climbing lanes. Chapter 8 reports the algorithm for the microcomputer program. Also an example application is provided, showing results of manual computations as well as those obtained from the microcomputer program.

Conclusions and recommendations are presented in Chapter 9. Finally, references used in this study are listed.

Chapter 2

RESEARCH FRAMEWORK

2.1 Requirements

This research required:

- the definition of the concept and theory of a cost-effectiveness methodology for the evaluation of climbing lane options (i.e., site, length, starting point),
- the development of methods for estimating delay and providing indicators of safety for climbing lane options,
- field studies yielding data for testing functions to be used for the estimation of level of service factors,
- development of a microcomputer-based program for analyzing safety and operational performance, and for cost-effectiveness evaluation of proposed climbing lane solutions on two lane highways.

2.2 Research Approach

In order to meet requirements for this study, a research framework was developed (Figure 2.1). The components of the framework are briefly described in this chapter. Details are covered in the following chapters 3 to 8 of this report.

2.2.1 The Cost-Effectiveness Methodology Framework

The overall methodology consists of four major elements. The first part of the model is devoted to the delineation of climbing lane options for a given site. The length of a climbing lane and its location within the roadway section are treated as variables. The methodology offers the flexibility of using a computerized procedure, based on a commonly used approach of starting the lane where the upgrade speed of a selected heavy vehicle drops below 15 km/h as compared to the approach speed, and ends where the speed comes back to within the 15 km/h differential. This approach would take a climbing lane over the crest. Another approach that could be used allows the climbing lane to end at crest.

The second component of the overall methodology is intended for the estimation of effectiveness measures (i.e., delay reduction, safety improvement). Techniques are to be developed

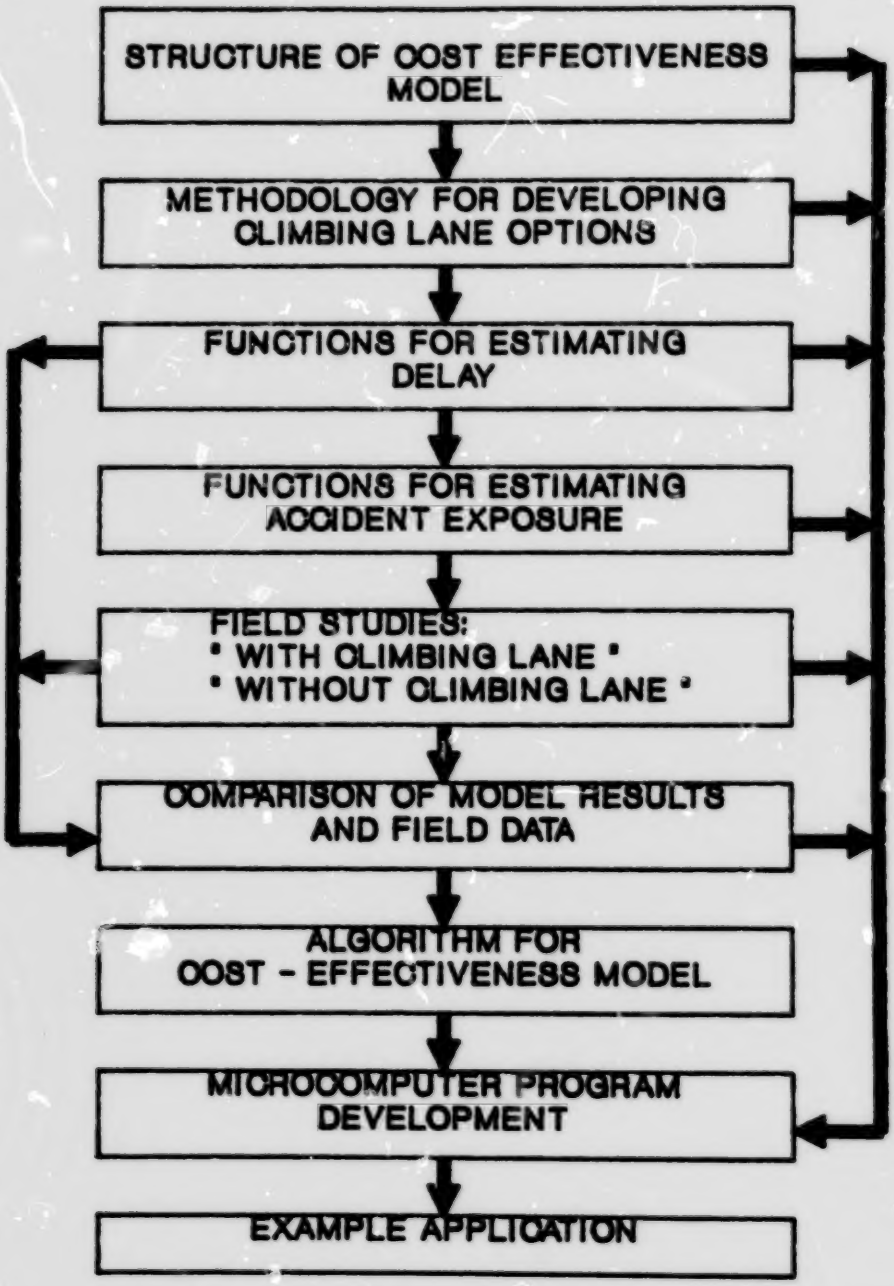

STRUCTURE OF COST EFFECTIVENESS MODEL
METHODOLOGY FOR DEVELOPING CLIMBING LANE OPTIONS
FUNCTIONS FOR ESTIMATING DELAY
FUNCTIONS FOR ESTIMATING ACCIDENT EXPOSURE
FIELD STUDIES:
* WITH CLIMBING LANE *
* WITHOUT CLIMBING LANE *
COMPARISON OF MODEL RESULTS AND FIELD DATA
ALGORITHM FOR COST - EFFECTIVENESS MODEL
MICROCOMPUTER PROGRAM DEVELOPMENT
EXAMPLE APPLICATION

Figure 2.1: Research Framework

that would enable the estimation of level of service and delay for given sites both with and without climbing lanes. Likewise estimators are to be provided that would give accident reduction information attributable to climbing lanes.

In the third component of the model, cost of climbing lanes is to be estimated. Guideline and techniques for costing are to be provided. The final part of the methodological structure is intended for cost-effectiveness assessment of climbing lane options. In addition to the study of cost-effectiveness, based on single as well as multiple measures, flexibility is to be provided for testing the economic feasibility of climbing lane options.

2.2.2 Technique for Developing Climbing Lane Options

A computerized technique is to be developed for establishing or characterizing climbing lane options, based on the following variables:

. length of climbing lane,
. location of climbing lane.

Candidate locations are to be defined for truck climbing lanes on the basis of critical length of grade. Depending upon user preference, this activity could be carried out manually and the required information could be provided as an input to the next methodological step.

2.2.3 Estimators of Level of Service and Delay

From the use of microscopic simulation models and data generated on upgrade sites, regression equations were developed that enable the estimation of speed and ultimately slow moving vehicle-induced delays. Variables that were considered and used for the development of functions are: length of roadway section, length of grade, percent grade, traffic volume and directional split, proportion of heavy vehicles in the traffic stream, and length of climbing lane.

The use of a microsimulation model for the generation of performance estimates was necessary in order to be able to vary various factors that affect the need and performance of climbing lanes and observe the effects.

2.2.4 Estimators of Safety

Safety improvements are an important consideration for the provision of climbing lanes. An attempt was made to obtain safety indicators of upgrade sections with and without climbing lanes. On the basis of available information, a method was developed for

estimating safety levels associated with climbing lane options under specified conditions.

2.2.5 Field Studies

Sites were identified that have climbing lanes and those that do not have climbing lanes. Out of a number of candidate sites for field studies, two were selected -- one with and one without a climbing lane. At these sites, measurements of speed drop and spot platooning were carried out. The field data were used for estimating "percent vehicles in platoons" and the average speed experienced by road users.

Speed readings were taken at the approach and upgrade. A video camera was used to record traffic characteristics on the upgrade part of the roadway section. The video tape was used to estimate average speed as well as the percentage of vehicles with headways (or time gaps) of 4 seconds or less. Manual counts of traffic volume were also carried out. Information on percent grade for each site was obtained from the regional office of the Ministry of Transportation, Ontario.

2.2.6 Validation of Performance Model

The intent of this part of the study was to check the validity of the traffic flow performance estimate obtainable from the use of regression equations. For each site, appropriate regression models were used to obtain indicators of level of service. Inputs to the models are the characteristics of the site and traffic. Estimates of percent vehicles in platoons and average speed upgrade were compared with information extracted from speed measurements and video tapes. In addition to a comparison with field data, other independent checks on the reliability of model results were carried out, including the use of Highway Capacity Manual (1985) procedures.

2.2.7 Algorithm for Cost-Effectiveness Methodology

As a prerequisite to the development of the microcomputer program, a detailed algorithm was required for the entire cost-effectiveness methodology. Three major components of the methodology were identified:

- Techniques for defining truck climbing lane length and location (i.e., starting and ending points),
- Information required for checking the fulfillment of warrants, and
- Techniques for assessing the cost-effectiveness of climbing lane options.

The design of the algorithm took into account user requirements for information on climbing lane planning, design and decision analysis. The methodology is made to be flexible so that user-specified analyses could be performed and sensitivity tests are permitted. In addition to cost-effectiveness analyses, as a user-specified option, the economic feasibility of climbing lanes (in net benefit terms) could be tested.

2.2.8 Development of Microcomputer Program

The cost-effectiveness methodology was implemented as a user-friendly micro-computer program, consisting of sub-programs or modules defined here as A to G. The program does not show these designations. Also, the program combines modules D to G.

- Module A: Input roadway and traffic characteristics
- Module B:
  - Input climbing lane option (length, location)
  - Computerized determination of climbing lane length and location
- Module C: estimate performance (i.e., speed, level of service) and check warrants,
- Module D: Effectiveness measures for each alternative,
- Module E: Cost of climbing lane,
- Module F (Optional): Economic feasibility of alternatives, sensitivity analysis,
- Module G: Cost-Effectiveness of alternatives and sensitivity analysis.

2.2.9 Example Application

This final step in the methodology was intended to illustrate the use of the microcomputer-based methodology by showing an example application.

Chapter 3

CLIMBING LANE OPTIONS: METHODOLOGICAL CONSIDERATIONS

3.1 Generation of Climbing Lane Options

Operational efficiency and safety considerations are used as a starting point for the identification of upgrade sections on two lane roads that could be regarded as candidates for climbing lanes. In the case of new construction, basic two-lane sections with an auxiliary lane on upgrade direction could be included as a part of construction plans. Since most two-lane highways are already built, such auxiliary lanes could be added as safety and operational improvement measures. Ultimately, climbing lanes and passing lanes (provided on level or rolling terrain sections of the highway) could become a part of twinning of the highway into a four lane cross section.

A climbing lane on a two-lane highway section, intended for the use of slow moving vehicles, offers the opportunity for other vehicles to continue their journey without being retarded. Platoons that form prior to the upgrade section are also offered the opportunity to pass slow moving vehicles without going into the opposing traffic lanes to complete such manoeuvers.

Climbing lane warrants investigated in an earlier study completed for the MTO include consideration of critical length of grade and a drop in level of service [1]. For the application of the critical length of grade concept, the first guideline suggests that a candidate section of a two lane highway should exceed the critical length of grade -- implying that the length of grade causes a reduction of 15 km/h or more in the speed of design truck (e.g., 180 kg/kw).

An additional guideline was used for the provision of a climbing lane. As compared to the design level of service for the highway (i.e., level of service B), owing to high traffic volume and the presence of heavy vehicles, a drop of one or more levels of service would warrant a climbing lane. That is, as compared to a level of service of B on the approach section, a level of service of C or worse on the upgrade section would call for the provision of a climbing lane.

Still another consideration is the added cost of providing climbing lanes as compared to their effectiveness [3]. It is understood that at sites where the critical length of grade is not exceeded, the influence of heavy vehicles on other traffic should be within the acceptable limit. At such sites, a climbing

lane would not be considered regardless of traffic volume. However, such sites could be examined for the provision of passing lanes.

On the other hand, for rural highways with very low traffic volumes, even though an upgrade section exceeds the critical length of grade and on that basis it may be desirable to consider a climbing lane, such an investment may not be economically justified.

Clearly, the process of defining climbing lane alternatives has to take into account the critical length of grade, safety, level of service, and cost guidelines for defining candidate sites for climbing lane [3].

3.2 Design Considerations

Auxiliary lanes could be considered for both directions of travel. However, their design for each direction is independent of the other. These may overlap or may not, depending upon the alignment and profile condition [3,4].

Most design manuals consider it desirable to provide a climbing lane on the upgrade side of a two lane highway, where the critical length of grade is exceeded and provided that the traffic is high enough to justify the added cost [3]. The MTO geometric design standards make a specific reference to critical length of grade for the design of climbing lane. It is stated as that combination of grade percent and length which will cause a designated design truck (e.g., 180 kg/kw) not to be able to maintain a speed which is 15 km/h below the prevailing highway speed. Lower speeds are not regarded acceptable for safety and operational efficiency reasons [5].

For new highways or those to be modified considerably, either the profile could be adjusted so that the gradient is no longer critical or an auxiliary (truck climbing) lane could be added for slow-moving vehicles. For existing highways, an auxiliary lane would the choice [5].

The length of climbing lane and the starting point have been of interest to researchers. Guidelines that are offered are noted below.

- The minimum length should enable a certain percentage of vehicles in a platoon to overtake the leader (i.e., slow vehicles)

- The truck speed criteria -- the point where an added lane should begin is a function of the approach speed of truck. In the absence of slow speed approaches, the extra lane may be

introduced some distance uphill -- a point where reduction in speed is 15 km/h. Prior to that point, the speed of truck is high enough so as not to cause intolerable conditions for following vehicles. This would be the consideration from the perspective of level of service and safety.

- If conditions permit, it would be desirable to extend the climbing lane to a point beyond crest. In some cases, it may not be practical because of the unduly long distance required for the heavy truck to regain speed which is 15 km/h below the approach speed.

- According to most guidelines, the climbing lane is terminated beyond crest of grade, enabling slow vehicles to resume normal speed. In such a design case, the fast moving vehicles are offered ample opportunities to overtake slow vehicles over the length of the climbing lane [6,7].

- For reasons of cost or construction difficulty, if a climbing lane has to be terminated on a upgrade (e.g., at crest), the merge area should be located beyond a point which offers the opportunity to see opposing traffic for sufficient distance to enable safe overtaking.

- In locations where sight distance restrictions, upgrade approaches, or other conditions suggest low speed of approaching trucks, the climbing lane may be introduced near the foot of the grade.

- Should two proposed short climbing lanes be close to each other, due to special feature of the terrain, these should be joined and one long auxiliary lane should be provided.

- Short climbing lanes should be avoided since truck drivers find it difficult to maintain desired operations of their vehicles on such lanes. Truck drivers may not use these at all, especially if they are familiar with the length of the lane [10].

- The beginning of the climbing lane should be preceded by a tapered section. The merge area also requires a taper.

- Road signs are necessary to advise drivers of the presence of a climbing lane ahead and to advise slow moving vehicles to take the right lane. A climbing should be so built so that it can be readily recognized as an extra lane in one direction. A climbing lane should be as wide as the through lane. The shoulder on the outer edge of a climbing lane should be of normal width provided on the normal two-lane section. Pavement markings should be clear.

As for the actual practice, the following observations have been drawn from the literature on the length of a climbing lane [8].

. The MTO practice suggests overtaking lanes to be between 1500 and 2000m in length. The tapers are 200m.

. The Province of B.C. uses 800m as the minimum length and 1000m as the desirable length for truck climbing lanes.

. In Australia, the climbing lane length varies with the design speed of the highway -- based on observation that most passing manoeuvers occur in the beginning part of the auxiliary lane [9]:
  - for 90 km/h, 500m (min)-700m (recommended)- 1000m (normal maximum), total tapers 225m,
  - for 100 km/h, 600m (min)-800m (recommended)- 1200m (normal maximum), total tapers 250m.

3.3 Methodology for Climbing Lane Design

3.3.1 Length of Climbing Lane

The distance from the bottom of the grade to the location where truck speed falls 15 km/h below the operating speed may be determined by the computer. The speed-distance functions for selected trucks could be stored in the form of tables and looked up as required. A computerized method of estimating the speed profile of a selected heavy vehicle would be much more expedient than the manual graphical or tabular procedure, based on the use of speed-distance functions.

The profile of the road section has to be specified and guidelines are to be developed on the treatment of composite grades. The approach speed of the selected heavy vehicle can be assumed to be equal to the average running speed on level road. For instance, a 180 kg/kw truck can be assumed to have an approach speed of 90 km/h to 93.8 km/h, even if the design speed of the highway is 100 km/h. According to speed-distance functions reported in reference 1, the highest speed on level road that could be attained by a truck of that type is 93.8 km/h. In the event of geometric design restrictions, the approach speed could be lower than the above amounts.

The use of the speed-distance tables/curves would enable tracking of speed as the truck traverses distance. For each section of constant grade, if that grade is negative, then the "acceleration downhill" tables/curves would be used. For positive grades, then either the "deceleration uphill" or "acceleration uphill" tables/curves would be applicable, depending upon the entry speed being greater than or less than, respectively, the maximum sustainable speed for that grade.

The actual algorithm used by a computerized version of this procedure is given below:

(1) Set entry speed to first section as 90 km/h.
(2) For each section of constant grade, do the following:
    (2.1) If grade is negative, use acceleration downgrade curve,
    (2.2) If grade is greater than or equal to zero, determine maximum sustainable speed for that grade. (This is the asymptotic speed in the speed-distance tables).
        (2.2.1) If entry speed is greater than or equal to maximum sustainable speed, then use deceleration upgrade curve or else use acceleration upgrade curve.
    (2.3) Use entry speed of section & selected speed-distance curve to calculate speeds & distance along section.
    (2.4) Set exit speed of this section as entry speed of the next section.

The computer program would enable the planner to develop a detailed knowledge of the speed profile of selected heavy vehicles. From such information, the length and location of a climbing lane could be inferred. That is, the starting and ending points of the climbing lane would correspond to the locations where the speed of a selected heavy vehicle drops by 15 km/h. The ending point would be where the speed comes back to within the 15 km/h speed difference.

Other methods for defining the length of a climbing lane could be based on sight distance, consideration of reducing the extent of platooning, especially on high volume routes, the use of a minimum length of climbing lane (e.g., 1.5 km for Ontario) for operational efficiency and safety reasons.

3.3.2 Starting and Termination Points

The truck speed drop criterion described above provides a basis for establishing the starting point for a climbing lane. The termination point could also be found through the use of the same criterion. Alternatively, the starting and/or termination points could be established on the basis of design judgement, taking into account the site-specific characteristics.

Should the designer wish to deviate from the formal procedure that would start a climbing lane some distance upgrade and terminate it at a point beyond crest, the computer method developed in this study is flexible enough to use such user-specified information as input for the follow-up analyses.

Chapter 4

ESTIMATION OF LEVEL OF SERVICE AND DELAY

4.1 Level of Service for Two Lane Highways

A major part of this study involved the development of methodology for estimating the level of service implication of providing climbing lanes on two lane roads. Much theoretical considerations were involved in the development of methodology, which enables an estimation of reduction in delay due to the provision of a climbing lane. Delay reduction is an accepted measure of the operational effectiveness of a climbing lane. Also, the definition of delay and delay reduction are consistent with Chapter 8 of the HCM (1985).

This section describes the state of knowledge in two lane highway level of service and highlights the need for new methodological developments required for estimating level of service for upgrade sections containing climbing lanes. The following sections provide details of the process followed for the development of new methodology.

The HCM (1985) procedures for the analysis of level of service of two lane highways are based on the following measures:

- percentage of travel time spent delayed -- being in platoons behind other vehicles,
- average travel speed,
- capacity utilization.

While it was recognized by the authors of the HCM (1985) that the first measure listed above would be a better indicator of driver-perceived quality of service, it is difficult to measure directly in the field and to make it operational for level of service analyses. A measure related to percent time delay is the percent of vehicles in platoons. Spot readings and therefore average of such spot readings could be obtained by observing the percent of vehicles travelling at headways less than 5 seconds (i.e., 4 seconds or less) [2].

Although the percent time delay ranges are specified by the HCM (1985) for the designation of various levels of service, corresponding average speed ranges are provided as well. These average speed guidelines, provided for level, rolling, and mountainous terrains, are used by analysts to estimate level of service of extended segments of two lane highways.

The HCM (1985) defined separate level of service criteria for specific grade segments in terms of average travel speed of vehicle climbing grades. While firm procedures for the analysis of downgrade sections are not specifically provided, guidelines are offered that suggest that [2]:

. downgrades less than 3% may be treated as level road,
. downgrades higher than 3% may considered to be the average of level roads and upgrade sections having the designated gradient.

Since the publication of the HCM (1985), a number of researchers have pointed out factors that are not covered by the HCM (1985) analysis procedures [11,12]. For instance, the HCM analysis procedures cannot be used for the assessment of roads with improved passing opportunities such as climbing lanes [11,12]. Also, it appears that the procedures for steep grades have not been harmonized with those for extended level sections. Furthermore, other measures of level of service have been suggested that are not described by the HCM (1985) (e.g., the ratio of achieved to desired overtaking, [13].

Thus, it was considered appropriate that in the use of the HCM (1985) procedures for the estimation of speed of vehicles at the approach to the grade and the average speed of vehicle on the upgrade section without climbing lanes, consistency checks should be made. For the analysis of sections with climbing lanes, new methodology had to be developed for the estimation of upgrade average speed for highway sections containing climbing lanes due to lack of available methodology for this task.

This chapter describes the available HCM (1985) procedures adopted in this investigation, and the development of new methodology, based on the use of a microscopic simulation model.

4.2 Estimation of Approach Speed

Approaches to upgrade sections of the highway have commonly zero grade. However, approach speeds may depend upon geometric design features, influencing sight distances. Rural two lane highways are designed for 100 km/h or 90 km/h. The average approach speed of vehicles on level road with a speed limit of 80-90 km/h under relatively low traffic volume and adequate geometric design conditions, might vary from slightly less than 90 km/h to middle 90s. In rare conditions, the approach speed may be different from this speed range, requiring special analysis of such cases.

Owing to the wide spread acceptance and use of HCM (1985) procedures, it was considered appropriate to estimate approach speed and level of service (LOS) by using these procedures for

level terrain. Steps to be followed are noted below:

. Estimate service flow (SF) rates for approach speeds (km/h): 90, 85, 80, 72, 68, 64, 56, 48. These speeds match closely the level of service gradations, as noted below.

. Compare the SF rates with DHV/PHF where PHF is the peak hour factor.

The user is expected to specify PHF (which is an indicator of peaking of traffic within the hour). A default value of PHF=1.0 is to be used, which suggests no peaking within the hour. As defined in the HCM (1985), the lower the PHF, the higher the peaking of traffic within the hour.

For each speed, there is a volume/capacity (v/c) ratio which can be used to estimate SF at a specified level of service i:

$SF_i = 2{,}800 \times (v/c)_i \times f_d \times f_w \times f_{hv}$

where

SF_i = total service flow rate in both directions for prevailing roadway and traffic conditions, for level of service i, in vehicles/h or vph;

$(v/c)_i$ = ratio of flow rate to ideal capacity for level of service i obtained from Table 4.1;

f_d = adjustment factor for directional distribution of traffic, obtained from Table 4.2;

f_w = adjustment factor for narrow lanes and restricted shoulder width, obtained from Table 4.3,

f_{hv} = adjustment factor for the presence of heavy vehicles in the traffic stream, computed as follows:

$= 1/[1 + P_T(E_T-1) + P_R(E-1)]$

- P_T = proportion of trucks in the traffic stream, expressed as a decimal,
- P_R = proportion of recreational vehicles (RVs) in the traffic stream, expressed as a decimal;
- E_T = passenger-car equivalent for trucks, obtained from Table 4.4;
- E_R = passenger-car equivalent for RVs, obtained from Table 4.4.

In the above equations, in theory, a $P_B(E_B-1)$ term could be added to account for buses. However, given the very small number of intercity buses or other buses that use two lane highways, this term was excluded from the above noted equation. In the

Table 4.1

Approach V/C For Various Levels of Service

LOS	Avg. Speed (Km/hour)	V/C Ratios* 0	20	40	60	80	100
A	≥ 93.4	0.15	0.12	0.09	0.07	0.05	0.04
B	≥ 90	0.27	0.24	0.21	0.19	0.17	0.16
C	≥ 84	0.43	0.39	0.36	0.34	0.33	0.32
D	≥ 80	0.64	0.62	0.60	0.59	0.58	0.57
E	≥ 72	1.00	1.00	1.00	1.00	1.00	1.00
F	< 72	-	-	-	-	-	-

* Apply to roads with design speeds of 100 km/h or higher; for design speed < 100 km/h, reduce average speed by about 6.5 km/h.
LOS A ≥ 86.9 km/h B ≥ 82.1 km/h C ≥ 77.3 km/h D ≥ 74.1 km/h
E ≥ 66.0 km/h F < 66.0 km/h

Source: HCM (1985)

Table 4.2

Correction Factor for Directional Split (f_d)

% Uphill Direction	100%	90%	80%	70%	60%	50%
f_d	0.71	0.75	0.83	0.89	0.94	1.00

Note: interpolate, if required.

Source: HCM (1985)

Table 4.3

Adjustment for Width and Other Geometric Design Features (f_w)

Usable Shoulder Width	3.66m Lanes		3.35m Lanes		3.05m Lanes	
	LOS A-D	LOS E	LOS A-D	LOS E	LOS A-D	LOS E
≥1.83m	1.00	1.00	0.93	0.94	0.84	0.87
≥1.22m	0.92	0.97	0.85	0.92	0.77	o.85

Source: HCM (1985)

Table 4.4

Passenger Car Equivalents (E_T & E_R)

LOS	E_T	E_R
A	2.0	2.2
B & C	2.2	2.5
D & E	2.0	1.6

Source: HCM (1985)

event that a very small number of buses are to be taken into account, such a vehicle may be regarded as a light truck.

4.5 Estimation of Upgrade Speed and Delay "Without Climbing Lane"

The HCM (1985) provides procedures for the estimation of upgrade speed without a climbing lane. In the case of composite grades, the weighted average grade can be found and used for subsequent computations. A single upgrade section followed by a level or a nearly level section is to be treated as a specific grade and can be used directly in the computation of speed and level of service. In the event that a positive grade of significant magnitude (i.e., 3% or higher) is followed by a relatively minor grade (i.e., plus and minus 1% or 2%) of considerable length, the averaging will tend to understate the importance of the specific grade section. Under such conditions, the presence of the downstream minor grade may be ignored.

The procedure for the estimation of average upgrade speed requires:

- the computation of SF for various speeds and levels of service, and
- comparison of SF with DHV/PHF in order to find average speed.

$$SF_i = 2{,}800 \times (v/c)_i \times f_d \times f_w \times f_g \times f_{hv}$$

where

f_d & f_w have been defined earlier,
f_g = adjustment factor for the operational effects of grades on passenger cars,
f_{hv} = adjustment for the presence of heavy vehicles in the upgrade traffic stream,
$(v/c)_i$ = volume-to-capacity ratio for level of service i, or speed i,

The equations for f_g and f_{hv} are shown below.

$f_g = 1/[1 + (P_p I_p)]$
$I_p = 0.02(E-E_0)$
E = base passenger-car equivalent for a given percent grade, length of grade, and speed,
E_0 = base passenger-car equivalent for 0% grade and a given speed,
I_p = impedance factor for passenger cars,
$f_{hv} = 1/[1+P_{hv}(E_{HV}-1)]$
P_{HV} = proportion of heavy vehicles in the upgrade traffic stream
$E_{HV} = 1+(0.25+P_{T/HV})(E-1)$
$P_{T/HV}$ = proportion of trucks among heavy vehicles.

Table 4.5

Level of Service for Upgrade Section

Level of Service	Average Upgrade Speed
A	≥ 90 km/h
B	≥ 80 km/h
C	≥ 72 km/h
D	≥ 64 km/h
E	≥ 40 - 64 km/h

Source: HCM (1985)

Service Flow (SF) rates are to be computed for the following speeds and level of service:

Level of Service	Average Upgrade Speed
A	90 km/h
B	85 km/h
B	80 km/h
C	72 km/h
D	64 km/h
E	48 km/h

Source: HCM (1985)

Table 4.6

Values of V/C vs.Speed, Percent Grade, and Percent No Passing Zones for Specific Grades

Percent Grade	Avg. Upgrade Speed (km/h)	Percent No Passing Zones					
		0	20	40	60	80	100
3	90	0.27	0.23	0.19	0.17	0.14	0.12
	85	0.42	0.38	0.33	0.31	0.29	0.27
	80	0.64	0.59	0.55	0.52	0.49	0.47
	72	1.00	0.95	0.91	0.88	0.86	0.84
	68	1.00	0.98	0.97	0.96	0.95	0.94
	64	1.00	1.00	1.00	1.00	1.00	1.00
4	90	0.25	0.21	0.18	0.16	0.13	0.11
	85	0.40	0.36	0.31	0.29	0.27	0.25
	80	0.61	0.56	0.52	0.49	0.47	0.45
	72	0.97	0.92	0.88	0.85	0.83	0.81
	68	0.99	0.96	0.95	0.94	0.93	0.92
	64	1.00	1.00	1.00	1.00	1.00	1.00
5	90	0.21	0.17	0.14	0.12	0.10	0.08
	85	0.36	0.31	0.27	0.24	0.22	0.20
	80	0.57	0.49	0.45	0.41	0.39	0.37
	72	0.93	0.84	0.79	0.75	0.72	0.70
	68	0.97	0.90	0.87	0.85	0.83	0.82
	64	0.98	0.96	0.95	0.94	0.93	0.92
	56	1.00	1.00	1.00	1.00	1.00	1.00

Notes: 1. Ratio of flow rate to ideal capacity of 2,800 pcph, assuming passenger-car operation is unaffected by grade.

2. Interpolate for intermediate values of "% no passing zone"; round "percent grade" to the next higher integer value.

Source: HCM (1985)

Table 4.6 (Continued)

Values of V/C vs. Speed, Percent Grade, and Percent No Passing Zones for Specific Grades

Percent Grade	Avg. Upgrade Speed (Km/h)	Percent No Passing Zones					
		0	20	40	60	80	100
6	90	0.12	0.10	0.08	0.06	0.05	0.04
	85	0.27	0.22	0.18	0.16	0.14	0.13
	80	0.48	0.40	0.35	0.31	0.28	0.26
	72	0.85	0.76	0.68	0.63	0.59	0.55
	68	0.93	0.84	0.78	0.74	0.70	0.67
	64	0.97	0.91	0.87	0.83	0.81	0.78
	56	1.00	0.96	0.95	0.93	0.91	0.90
	48	1.00	0.99	0.99	0.98	0.98	0.98
7	90	0.00	0.00	0.00	0.00	0.00	0.00
	85	0.13	0.10	0.08	0.07	0.05	0.04
	80	0.34	0.27	0.22	0.18	0.15	0.12
	72	0.77	0.65	0.55	0.46	0.40	0.35
	68	0.86	0.75	0.67	0.60	0.54	0.48
	64	0.93	0.82	0.75	0.69	0.64	0.59
	56	1.00	0.91	0.87	0.82	0.79	0.76
	48	1.00	0.95	0.92	0.90	0.88	0.86

Notes: 1. Ratio of flow rate to ideal capacity of 2,800 pcph, assuming passenger-car operation is unaffected by grade.

2. Interpolate for intermediate values of "% no passing zone"; round "percent grade" to the next higher integer value.

Source: HCM (1985)

Table 4.7

Adjustment for Directional Distribution of Traffic (f_d)

Percent of Traffic Upgrade	Adjustment Factor f_d
100	0.58
90	0.64
80	0.70
70	0.78
60	0.87
50	1.00
40	1.20
≤30	1.50

Source: HCM (1985)

Table 4.8

Passenger Car Equivalent for Specific Grades on Two-Lane Rural Highways, E and E_0

Grade (%)	Length of Grade (km)	Average Upgrade Speed (km/h)					
		90	85	80	72	64	48
0	All	2.1	1.8	1.6	1.4	1.3	1.3
3	0.40	2.9	2.3	2.0	1.7	1.6	1.5
	0.81	3.7	2.9	2.4	2.0	1.8	1.7
	0.21	4.8	3.6	2.9	2.3	2.0	1.9
	1.61	6.5	4.6	3.5	2.6	2.3	2.1
	2.42	11.2	6.6	5.1	3.4	2.9	2.5
	3.22	19.8	9.3	6.7	4.6	3.7	2.9
	4.83	71.0	21.0	10.8	7.3	5.6	3.8
	6.44	*	48.0	20.5	11.3	7.7	4.9
4	0.40	3.2	2.5	2.2	1.8	1.7	1.6
	0.81	4.4	3.4	2.8	2.2	2.0	1.9
	1.21	6.3	4.4	3.5	2.7	2.3	2.1
	1.61	9.6	6.3	4.5	3.2	2.7	2.4
	2.42	19.5	10.3	7.4	4.7	3.8	3.1
	3.22	43.0	16.1	10.8	6.9	5.3	3.8
	4.83	*	48.0	20.0	12.5	9.0	5.5
	6.44	*	*	51.0	22.8	13.8	7.4
5	0.40	3.6	2.8	2.3	2.0	1.8	1.7
	0.81	5.4	3.9	3.2	2.5	2.2	2.0
	1.21	8.3	5.7	4.3	3.1	2.7	2.4
	1.61	14.1	8.4	5.9	4.0	3.3	2.8
	2.42	34.0	16.0	10.8	6.3	4.9	3.8
	3.22	91.0	28.3	17.4	10.2	7.5	4.8
	4.83	*	*	37.0	22.0	14.6	7.8
	6.44	*	*	*	55.0	25.0	11.5

* Speed not attainable on grade specified.

Note: Round "% grade" to next higher integer value.

See next page for grades 6% and 7%.

Source: HCM (1985)

Table 4.8 (Continued)

Passenger Car Equivalent for Specific Grades on Two-Lane Rural Highways, E and E_0

Grade (%)	Length of Grade (km)	Average Upgrade Speed (km/h)					
		90	85	80	72	64	48
6	0.40	4.0	3.1	2.5	2.1	1.9	1.8
	0.81	6.5	4.8	3.7	2.8	2.4	2.2
	1.21	11.0	7.2	5.2	3.7	3.1	2.7
	1.61	20.4	11.7	7.8	4.9	4.0	3.3
	2.42	60.0	25.2	16.0	8.5	6.4	4.7
	3.22	*	50.0	28.2	15.3	10.7	6.3
	4.83	*	*	70.0	38.0	23.9	11.3
	6.44	*	*	*	90.0	45.0	18.1
7	0.40	4.5	3.4	2.7	2.2	2.0	1.9
	0.81	7.9	5.7	4.2	3.2	2.7	2.4
	1.21	14.5	9.1	6.3	4.3	3.6	3.0
	1.61	31.4	16.0	10.0	6.1	4.8	3.8
	2.42	*	39.5	23.5	11.5	8.4	5.8
	3.22	*	88.0	46.0	22.8	15.4	8.2
	4.83	*	*	*	66.0	38.5	16.1
	6.44	*	*	*	*	*	28.0

* Speed not attainable on grade specified.

Note: Round "% grade" to nearest higher integer value.

Source: HCM (1985)

The level of service and speed correspondence for upgrade sections without a climbing lane is shown in Table 4.5. Values of v/c ratios vs. speed are noted in Table 4.6. The f_w values are given in Table 4.3. Table 4.7 presents the f_d factors. The values for passenger car equivalents (i.e., E & E_0) for specific grades are presented in Table 4.8.

4.4 Estimation of Upgrade Speed and Delay With Climbing Lane

The HCM (1985) does not offer guidelines and procedures for estimating speed, delay and level of service for upgrade sections containing climbing lanes. Phase I of this project used the assumption of "one level of service improvement" arising from the provision of a climbing lane. In this phase II, regression equations were developed which are to be used to estimate the change in upgrade speed attributable to climbing lanes.

The regression equations are to be used to estimate changes in speed caused by climbing lanes. This information is to be used in conjunction with HCM (1985) procedures to estimate speed and level of service of upgrade sections containing climbing lanes. In the following sections of this chapter, the process for the development of new techniques and the resulting equations and guidelines are described. Chapter 7 provides an example application.

4.4.1 Simulation of Highway Performance: The Approach

A microscopic simulation model, namely TWOPAS model, was used for simulating the performance of a large number of two lane road sections containing grades. Variables used for simulating the performance of two lane road sections, and ultimately for the development of regression equations, are:

- percent grade
- length of grade/roadway section
- traffic volume
- directional split (percent traffic in the upgrade direction)
- percent trucks (or number of trucks)
- percent recreational vehicles (RVs) (or number of RVs)
- length of climbing lane (if applicable)
- overtaking allowed/not allowed

4.4.2 Selection of Microscopic Simulation Model

Two microscopic simulation models were considered. The first model acquired was the TWOPAS model. This model, developed by the Midwest Research Institute for the Federal Highway Administration (U.S.A.), simulates traffic operations on two lane highways by reviewing position, speed, and acceleration of each vehicle and advances vehicles on the roadway [14]. An earlier version of this

model was used extensively for the development of material contained in the two lane rural highway chapter of the HCM (1985).

The model simulates traffic operations in detail, based on traffic and roadway characteristics selected by the user. Roadway parameters include characteristics such as passing restrictions, auxiliary lanes, horizontal and vertical curves or variables that influence sight distance. Vehicle characteristics include parameters such as vehicle power and weight characteristics or driver characteristics. Traffic parameters include volume, speed, and directional split. Model outputs are numerous, including spot speed, the number of overtakings, measures of platooning and average speed.

At the time of selecting a microscopic simulation model, the TWOPAS model was compared with the TRARR model, developed by the Australian Road Research Board [15]. The TRARR model is generally similar to the TWOPAS model. The TWOPAS model is implemented on a main frame computer whereas the TRARR version tested for the present study can run on a microcomputer.

Both models simulate traffic operations in detail based on traffic and roadway characteristics selected by the user. Up to 18 vehicle types can be simulated by TRARR and 13 vehicle types by TWOPAS. In the case of TWOPAS model, although average approach speed can be specified, the distribution of speeds for each category of vehicle is represented according to a truncated normal probability distribution function.

The TWOPAS model has more outputs than TRARR, such as overall speed histograms, time margins and aborts, and headway and platooning summary. A comparison of the two models based on similar inputs is shown in Table 4.9.

As results suggest that due to the similar nature of the models and also some differences in inputs required for the two models, there are both similarities and differences in outputs. The average speed, delay and platooning characteristics are generally similar whereas "percent time following" values are different. Another reason for such a difference is the different definitions of this performance indicator.

4.4.3 Development of Macroscopic (Regression) Models

On the basis of model capabilities and familiarity with the program outputs, it was decided to use the TWOPAS model for production runs.

The TWOPAS Model incorporates a large number of features of the road, vehicles, driver and traffic. A number of these

Table 4.9

Comparison of TWOPAS and TRARR Models

Inputs:
Two lane highway; 2% grade, length of grade is 2000m; Climbing lane is 1500m; Volume is 800 vph with 70% of traffic travelling upgrade; The traffic volume consists of 15% trucks and 5% recreational vehicles. Simulation time: 1200 seconds.

Selected Outputs:

	TWOPAS	TRARR
Overall average speed:		
Direction 1 (upgrade)		
- Trucks	79.1 km/h	85.1 km/h
- RVs	78.7	75.2
- Automobiles	86.4	86.2
Direction 2		
- Trucks	90.7	91.3
- RVs	83.3	75.4
- Automobiles	85.8	89.2
Delay *		
Direction 1 (upgrade)		
- Trucks	4.5	1.4
- RVs	4.4	6.5
- Automobiles	1.3	1.8
Direction 2		
- Trucks	no delay	no delay
- RVs	1.9	6.4
- Automobiles	2.0	0.4

* As defined in this case, delay is the time difference between travel time by overall average speed and the travel time by average desired speed.

Table 4.9 (Continued)

Comparison of TWOPAS and TRARR Models

	TWOPAS	TRARR
Platoons **		
Direction 1 Size		
1	53	53
2	24	26
3	8	10
4	7	5
Direction 2 Size		
1	41	27
2	9	10
3	2	9
4	2	4
Percent Time Spent Following		
Direction 1		
- Trucks	9.8+	34.5
- RVs	4.1	24.3
- Automobiles	13.3	32.0
Direction 2		
- Trucks	33.1	36.6
- RVs	8.4	31.2
- Automobiles	29.0	41.6

** As defined here, a vehicle is in platoon if its headway is less than or equal to 4 seconds. Platoon size includes both the platoon leader and the platoon members.

+ "% time following" is transferred from percent of time unimpeded in the output of TWOPAS.

features are to be specified by the user. Also, program logic takes care of numerous inputs. Default values are also available for use in specific simulation runs [11].

Geometric and other features of the highway that are treated include: grades, horizontal curves, lane width, shoulder width, pavement quality, passing sight distance, and passing and climbing lanes. Traffic control information that is included in the program logic includes: passing and no-passing zones, passing and no-passing zones in the opposing direction to a passing or climbing lane, and speed limit (user-specified). Vehicle characteristics that are included in the model are: acceleration and speed capabilities (assigned to 13 vehicle types) and length (assignable for each of the 13 vehicle types).

Driver characteristics and preferences incorporated in the model are: desired speeds (assigned stochastically from a truncated normal distribution with user specified mean and standard deviation), preferred acceleration levels, sustained use of maximum power performance, examination of passing possibilities, acceptance/rejection of passing opportunities, extend pass in progress to additional impeder, behaviour while passed, and behaviour in passing and climbing lane sections.

Entering traffic features that are included are: flow rates, vehicle mix, platooning in entering traffic stream, and immediate upstream alignment. Within each vehicle category (i.e., trucks, RVs, cars), the distribution was set to correspond to Ontario conditions [1]. For example the heavy truck was set to be equal to 12.6% of truck traffic.

The mean desired speed was set to correspond to the speed limit on the highway, namely 90 km/h. For sensitivity tests, this speed was raised to 100 km/h. Standard deviation of desired speeds were also specified.

As for the specification of the extent of platooning at the approach to the highway section on grade, the variable of "percent of vehicles" following a platoon leader was used. Its value was varied, depending upon the service flow that was to be accommodated. The values of "% following" for corresponding service flow rates were set in accordance with guidelines contained in the program. Default values were used for initial trial runs. The highest value of "% following" used amounted to 74%, which corresponded with a service flow of 1348 vehicles per hour.

A number of special features of the TWOPAS model are summarized below.

. The initial lane choice of driver entering a passing lane is based on: the geometrics of the auxiliary lane; the speed, performance capabilities, and size of the vehicle; and traffic situation at the time of decision [12].

. Lane choice probabilities (for passing and climbing lane contexts) are based on extensive field data).

. Lane changing is realistic in the context of climbing/passing lane sections.

. Operation of the merge area (lane drop area) is based upon driver behaviour observed in the field.

. Generation of entering traffic headway is based on Borel-Tanner distribution for platoon sizes [12].

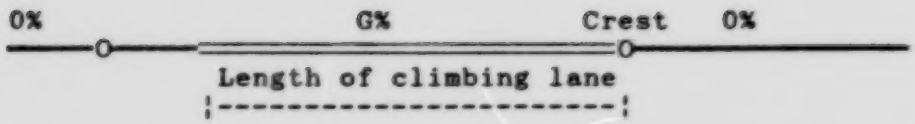
. A negative exponential distribution is used for interplatoon headway.

In the absence of information on a large number of sites that are with and without climbing lanes, and the lack of required input information, it was decided to carry out a random selection of roadway and traffic features. For each variable of interest, a realistic set of values were defined (e.g., DHV values ranging from 100 to 1500 vph). Following discussions with the Statistical Consultation Centre, Carleton University, a random selection procedure was adopted for developing information for case sites. These information items were used as inputs to the TWOPAS model.

The results of the TWOPAS model are the performance indicators of the roadway sections that were simulated. These outputs were used for the development of regression models of upgrade performance of sites tested. Two options for the location of climbing lanes were pursued (Figure 4.1):

. climbing lane ending beyond crest, and
. climbing lane ending at crest.

The length beyond crest was set at 30% of total length of climbing lane for all test cases. In order to make the results comparable for two options of climbing lane location, same length of L_A and L_B as well as same data set were used. The results from multiple regression models show that better performance is achievable from the simulated roadway sections if climbing lane is carried beyond crest.



Length of climbing lane

Length of road section of interest L_A

Climbing Lane Ending At Crest

Length of climbing lane

Length of road section of interest L_A

Climbing Lane Ending Beyond Crest

Figure 4.1: Climbing Lane Configurations

The inputs to the TWOPAS model (i.e., road and traffic data) were used as independent variables for the development of regression models of upgrade performance. The results of TWOPAS models were used as the dependent variables. The data are grouped according to the presence or absence of climbing lane, location of climbing lane and roadway characteristics. Dependent variables considered were the average speed, spot speed, time following, percent of vehicles in platoons, and delay (defined differently as compared to the definition adopted in this study). Independent variables included volume, directional distributional of traffic, percent grade, length of grade/road section, percent trucks, percent RVs, and length of climbing lane. Results are shown in Table 4.10.

4.4.4 Estimation of Upgrade Speed With A Climbing Lane

A blending of the HCM (1985) procedures and the regression models of road performance provides a method for estimating upgrade speed with a climbing lane. The steps to be followed are listed below:

1. Estimate average upgrade "without climbing lane" by using HCM (1985) procedure (Section 4.3).

2. (a) Estimate upgrade average speed by using regression equations for "without climbing lane" case (Table 4.10).
   (b) Estimate upgrade average speed by using regression equations for "with climbing lane" case (Tables 4.11 & 4.12).
   (c) Find gain in speed due to climbing lane (b-a).

3. Add the gain in speed as found in 2(c) to average upgrade speed "without climbing lane" found in step 1. This new speed should be checked against approach speed and speed without climbing lane according to the guidelines noted below and the logic diagram shown as Figure 4.2.

Guideline 1:
The approach speed should be higher than or equal to the upgrade average speed without a climbing lane.

Discussion:
A deficiency of Chapter 8 of the HCM (1985) is that the speed and level of service criteria for level terrain and those for upgrade are, at times, not consistent. For a higher speed on the level approach, the level of service may be specified to be lower than the level of service upgrade with a lower speed. Another inconsistency might arise when approach speed may turn out to be less than average upgrade speed. Consequently, it is necessary to check speeds on level approach and upgrade in order to ensure that the approach speed is not less than the average upgrade

Table 4.10

Regression Equations for Estimating Average Upgrade Speed Without Climbing Lane

---

Without Climbing Lane; Passing Allowed (0% No Passing Zones)

Avg. Upgrade Speed (km/h) = 127.473916 - 0.015989 (Two-Way Vol.)
- 0.129015 (% Traffic Upgrade Direction) - 5.061259 (% Grade)
- 0.005077 (Length of Grade in m) - 0.274405 (% Trucks)
- 0.218653 (% RVs)

R^2 = 0.82
N = 56

Without Climbing Lane; Passing Not Allowed (100 No Passing Zones)

Avg. Upgrade Speed (km/h) = 125.378202 - 0.015989 (Two-way Vol.)
- 0.129015 (% Traffic Upgrade Direction) - 5.061259 (% Grade)
- 0.005077 (Length of Grade in m) - 0.274405 (% Trucks)
- 0.218653 (% RVs)

R^2 = 0.82
N = 56

Notes:

1. The above equations are identical except for the constant term. These equations were developed by using a dummy variable for overtaking condition.

2. For % no passing zones that fall between 0 and 100, interpolation of upgrade average speed will require the following procedure.

   For an upgrade section containing x% no passing zones:

   Avg. upgrade speed for x% no passing zones =
   (1/100)[(100-x)(speed for case when overtaking is allowed)
   + (x)(speed when overtaking is not allowed)]

Table 4.11

Regression Equations for Estimating Upgrade Average Speed With Climbing Lane, Climbing Lane Ending Beyond Crest

Passing Allowed (0% No Passing Zones)

Upgrade Avg. Speed (km/h) = 118.931681 - 0.003619 (Two-way Vol in vph) - 5.208277 (% grade) - 0.009991 (Length of Grade in m) + 0.008401 (Length of Climbing Lane in m) - 0.009316 (Car Volume Upgrade direction, vph) - 0.05421 (Truck Vol. Upgrade Direction, vph) - 0.002823 (RV Vol. Upgrade Direction, vph)

R^2 = 0.89
N = 38

Passing Not Allowed (100% No Passing Zones)

Upgrade Avg. Speed (km/h) = 117.951135 - 5.45491 (% Grade) - 0.010884 (Length of Grade in m) + 0.009575 (Length of Climbing Lane in m) - 0.014782 (Car Volume Upgrade, vph) - 0.061663 (Truck Volume in the Upgrade Direction, vph) - 0.001976 (RV Volume in the Upgrade Direction, vph)

R^2 = 0.90
N = 36

Note: For % no passing zones that fall between 0 and 100, the following interpolation methods is to be used.

Avg. speed upgrade for x% no passing zones =
(1/100)[(100 - x)(speed when overtaking is allowed) + (x)(speed with no overtaking)]

Table 4.12

Regression Equations for Estimation of Upgrade Average Speed
Climbing Lane Ending At Crest

Overtaking Allowed (0% No Passing Zones)

Upgrade Avg. Speed (Km/h) = 118.851198 - 0.001383 (Two-way Vol. in vph) - 0.005802 (Length of Grade, in m) - 4.443712 (% Grade) + 0.007687 (Climbing Lane in m) - 0.606146 (Trucks, % for Both Directions) - 0.020814 (RV Vol. in the Upgrade Direction, vph) - 0.031306 (Car Vol. in the Upgrade Direction, vph)

R^2 = 0.88
N = 36

Overtaking Not Allowed (100% No Passing Zones)

Upgrade Avg. Speed (km/h) = 119.107887 - 0.000433 (Two-way Vol. in vph) -0.006886 (Length of Grade, in m) - 4.641518 (% Grade) + 0.008912 (Climbing Lane in m) - 0.615856 (Trucks, % for Both Directions) - 0.022193 (RV Vol. in the Upgrade Direction, vph) - 0.035963 (Car Vol. in the Upgrade Direction, vph)

R^2 = 0.89
N = 36

Note: For % no passing zones that fall between 0 & 100, the following interpolation procedure is to be carried out.

Avg. speed upgrade for x% no passing zones =
(1/100)[)((100-x)(speed when overtaking is allowed)
+ (x)(speed when overtaking is not allowed)]

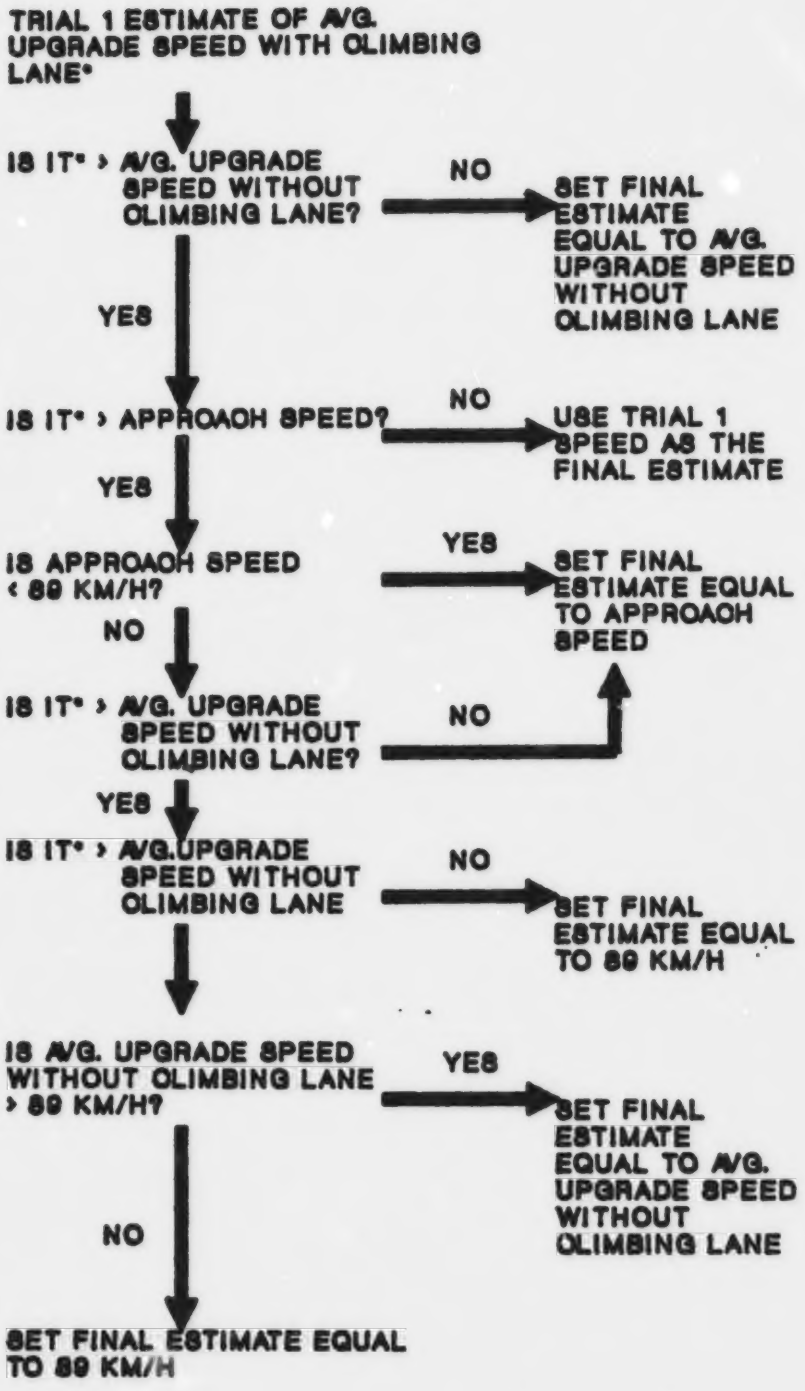


Figure 4.2: Algorithm for Speed Adjustment

speed without a climbing lane. For rare situations where due to sight distance or other constraints, the approach speed might be low and vehicles might gain speed on the uphill section of the road, the present procedure will not be applicable.

Guideline 2:
The upgrade average speed with a climbing lane should be greater than or equal to upgrade average speed without a climbing lane.

Discussion:
The rationale for this check is that the procedures for determining the upgrade average speed with and without climbing lane have to be harmonized. The HCM procedures are to be used for analyzing upgrade sections without a climbing lane. On the other hand, new methodology has been developed for estimating the gain in operational performance (i.e., average speed) that is expected from the provision of a climbing lane. It is logical that the two sets of procedures have to be harmonized.

Guideline 3:
A third guideline is that the upgrade average speed with a climbing lane should be less than or equal to 90 km/h (i.e., the speed limit).

Discussion:
For the overall traffic stream, given their average gradeability characteristics, it is logical to expect that an uphill section with a critical length of grade, even with a climbing lane would not offer a level of service better than the lower limit of level of service A. For two lane highways with posted speed of 90 km/h this guideline is a reasonable one.

In the above noted methodology, the average speed is used for the study of improvements in level of service obtainable from climbing lanes. As noted in the introductory section of this chapter, this measure is also used by the HCM (1985) for specific grades. Other indicators of level of service for two lane highways, namely "percent time following" and "percent of vehicles in platoons" cannot be used directly to quantify operational effectiveness in terms of time and delay reduction. It is recognized here that even if the operating speed of the road is high enough, a high degree of platooning would be regarded as undesirable by road users. Table 4.13 provides regression equations that were developed for the estimation of % vehicles in platoons. However, at present, there is no method available that could be used to translate % vehicles in platoons into delay encountered by road users.

4.5 Estimation of Delay

Delay to vehicles on the upgrade sections is defined as the

Table 4.13

Regression Equations for Estimating Percent of Vehicles in Platoons

Without Climbing Lane; Overtaking Allowed/Not Allowed*

% vehicles in Platoons = - 19.0979
+ 0.0361 (volume, veh/h)
+ 0.2553 (% traffic upgrade)
+ 2.8475 (% grade)
+ 0.0025 (length of section, m)
+ 0.3090 (% trucks)
+ 0.3453 (% RVs)
+ 5.7143 (dummy variable for overtaking allowed or not allowed)
Use 0 for overtaking allowed
Use 1 for overtaking not allowed

R^2 = 0.78
N = 56

* This equation uses a dummy variable for overtaking condition

With Climbing Lane; Overtaking Allowed

% vehicles in Platoons = + 23.32008
+ 0.003735 (volume, veh/h)
+ 0.047768 (car volume per hour)
+ 0.11863 (% grade)
+ 0.004853 (length of section, m)
- 0.009912 (climbing lane length, m)
+ 0.038082 (truck volume per hour)
+ 0.027186 (volume of RVs per hour)

R^2 = 0.90
N = 38

With Climbing Lane; Overtaking Not Allowed

% vehicles in Platoons = + 25.025218
+ 0.553825 (% grade)
+ 0.005504 (length of section, m)
- 0.011914 (climbing lane length, m)
+ 0.046758 (car volume per hour)
+ 0.050263 (truck volume per hour)
+ 0. 050832 (volume of RVs per hour)

R^2 = 0.86
N = 35

difference in time required to traverse the upgrade section under the prevailing conditions and the time that would be involved should the road users be able to maintain their approach speed. The steps required to quantify the change in delay attributable to a climbing lane are given here.

1. Define roadway section length (km) of interest.
2. Define AADT (veh/day). Also show DHV for reference purposes.
3. Determine approach speed (km/h) (Section 4.2).
4. Determine upgrade average speed (km/h) without a climbing lane.
5. Determine upgrade average speed (km/h) with climbing lane.
6. Determine delay/year (hours) without and with a climbing lane:

   Delay/yr (hrs) = (Delay/veh in sec) x AADT x % Upgrade Volume x 365 x (1/3600)

   where

   Delay/veh (sec) = [(3600/upgrade speed in km per hour) - (3600/approach speed in km per hour)] x (length of roadway section in kms)
7. Determine change in delay/year (hrs) = delay without climbing lane - delay with climbing lane.

4.6 Warrants for Climbing Lane

Climbing lane warrants were reviewed in a previous study carried out for the MTO. The factors that are considered in decision making are: safety of road users, operational efficiency (i.e., minimization of delays caused by slow vehicles on grade), and cost of providing climbing lanes [1]. The MTO warrants include safety and operational efficiency. Safety improvements attributable to climbing lanes are discussed in Chapter 5 of this report.

Operational efficiency improvements on two lane highways that are made possible by climbing lanes include the reduction of percent time delay, increased average travel speed, and reduced platoons. The operational efficiency objective is pursued through the consideration of level of service on grade. Guidelines suggest that should the level of service upgrade drop by one or more than one intervals below the design level of service for the highway, a climbing lane should be considered for that site. Considering that the design level of service for rural highways is B, a level of service of C or worse could be considered as a basis for constructing a climbing lane [1].

The cost variable has not been treated formally in the past. The cost-effectiveness methodology described in Chapter 7 is intended to improve the efficient use of infrastructure investment capital by combining operational effectiveness, safety effectiveness and cost of climbing lanes.

Chapter 5

SAFETY EFFECTIVENESS OF CLIMBING LANES

5.1 Causes of Accidents on Grade

Early studies on two lane highway safety suggest the awareness that a drop in speed upgrade caused by slow moving vehicles, as compared with the prevailing highway speed, could be used to explain accident causation on grade. Within the upgrade traffic stream, much difference in the speed of various vehicle types creates safety hazards. The higher the deviation of speed of slow vehicles from the average speed, the greater the probability of their involvement in accidents. The higher the speed differential between the upgrade average speed and the approach speed, the higher the risk of accidents [10]. Early statistics indicate that as the gap between upgrade speed and the average speed of highway increased, the higher was the accident involvement rate [10].

The reason for increased safety hazard under conditions of decreasing speed relates to unsafe manoeuvers that are made while passing slow moving vehicles. Logically, the provision of climbing lanes should enhance safety by providing a widened roadway and by enabling overtaking manoeuvers away from the path of opposing traffic. Should the merge areas be designed properly and adequate sight distance be provided, the climbing lanes should be able to provide enhanced safe driving conditions on two lane roads.

A reduction in traffic conflicts involved in the passing manoeuvers on two lane cross sections through the provision of passing opportunities should reduce driver frustration and hazardous manoeuvers. Increased fulfillment of demand for overtaking slow vehicles should in theory increase safety.

The activity of overtaking a slow vehicle, among other factors, is influenced by the length of vehicle being overteken as well as that of the vehicle initiating the manoeuver. Conceptually, in the absence of an appropriate distance over which the passing manoeuvre could be completed when long vehicles are present in the traffic stream, a safety hazard may be encountered.

In the following section, recent studies on safety of two lane highways are reviewed from the perspective of assessing safety effectiveness of climbing lanes. Past studies have not covered all potential causes of accidents noted above. Therefore, the subject of safety of two lane highways in the context of

overtaking is worthy of further investigations. In this project, the intent is to develop a method, based on empirical evidence, for the estimation of safety effectiveness of climbing lanes. Obviously, a better insight into the subject of safety and improved accident data base could be used in the future to update the methodology reported in this chapter.

5.2 State of Knowledge: Recent Studies

A limited number of recent studies have researched safety of climbing/passing lanes. Most have found favourable safety effects of such provisions on two lane highways [16,17]. Findings of recent studies are summarized here. It should be noted that most investigations have treated the subject of safety of auxiliary lanes in a unified manner, without being specific about the gradient of the highway section containing such lanes.

- A U.S. study (based on a small sample of climbing lanes), reported by Jorgensen found no change in accidents attributable to climbing lanes [18].

- A U.K. study by Martin and Voorhees Associates found a 13% drop in accidents due to the construction of climbing lanes [19].

- A California study, reported by Rinde examined 23 sites in level, rolling, and mountainous terrain and found a reduction in accidents amounting to 11 to 27%, depending upon road geometrics. The accident rate reduction experience for 13 sites in level or rolling terrain was highly favourable -- showing 42% reduction [20].

- Data from 22 sites in four states examined by Harwood and St.John showed an accident rate reduction effectiveness of passing lanes to be 9% for all accident and 17% for fatal and injury accidents. On the basis of the combined data from a number of studies, the authors concluded that passing lane installations reduce accident rate by 25% [11,12].

- Safety studies have found no special problem areas on sites with climbing lanes. Field studies of traffic conflict and erratic manoeuvers at the lane drop transition areas of climbing/passing lanes show that these were found to operate smoothly. Overall, a very small percentage (i.e., 1.3%) of the vehicles passing through the lane drop transition zone created a traffic conflict. Erratic manoeuver rates of 0.4% and 0.3 % were observed for centreline and shoulder encroachment, respectively [11,12].

- Investigations of cross-centreline accidents involving vehicles travelling in opposite directions on the highway uncovered no safety differences between passing lanes, and sites where

passing was prohibited in the opposing direction, provided that sight distance was adequate. The provision of overtaking by vehicles travelling in the opposite direction did not appear to have caused any safety problems at properly designed sites and volume levels of 400 veh/hr in one direction of travel. Accident rates for the climbing/passing lane area and cross-centreline accident rates at such sites were lower than those of comparable sections of conventional two lane highway [11,12,21].

- Harwood et. al. (1985) made a matched pair comparison between 13 passing lane sites and 13 corresponding untreated sites. Results suggest that in all but two cases, sections with auxiliary lanes had a lower accident rate, although the observed differences for fatality and injury rates were not statistically significant [21].

- Safety studies in Sweden, applicable to climbing lanes on two lane roads, show that accident rate reduction on the grade and some distance beyond crest varies from 0 to 1.75 accidents per million passenger vehicle km. [16].

To summarize, past studies suggest that:

- climbing/passing lane installations have been credited with a reduction in accident rates by 25% or higher as compared with untreated two-lane sections [15],

- lane addition (diverge) and (merge) areas do not present any marked safety hazards,

- lane drops on an up grade would not be a safety hazard if there is adequate passing site distance at lane drop, and

- inadequate sight distance prior to the lane drop creates a safety hazard. At these locations, the sight distance should be sufficient for a vehicle to stop in case of a problem.

5.3 Role of Climbing Lanes in Improving Safety: Experience of Transportation Agencies

On the basis of convincing statistics, it is widely recognized that there is a direct relationship between accidents and speed differences between adjacent sections of a highway and within a traffic stream. As a result, transportation agencies have initiated programs of increasing the opportunities for vehicles to pass heavy slowing moving vehicles on up grades. The provision of climbing lanes has reduced platooning and also improved average speed [7].

Experience of transportation agencies suggests that climbing lanes are generally used by slow moving vehicles, thus offering the opportunity to faster traffic to continue in the through lane. In the absence of slower moving vehicles that are to be overtaken, some faster traffic may use the climbing lane.

Initially, there were concerns that potential safety hazards could develop at upper terminals of climbing lanes (i.e., merge points), especially on upgrade sections. At such locations, vehicles travelling at substantially different speeds have to merge (i.e., a slow heavy vehicle merging with main traffic stream). However, through the provision of adequate sight distance and proper design of merge sections, safety hazards could be reduced.

As indicated in Chapter 4, the length of a climbing lane is one among many variables that influence the effectiveness of a climbing lane in dissipating platoons. It is logical that:

- the effect of length and location of climbing lanes under given traffic, geometric design, and traffic control (i.e., overtaking allowed/not allowed) conditions on operational performance of upgrade sections be found first,

- then, on the basis of operational performance, as captured by a lessening of the average speed differential between upgrade and approach sections, safety implications of climbing lanes can be found.

5.4 Methodology for Estimating Accident Involvement Rates

A method was developed for the estimation of safety levels associated with climbing lane options under specified conditions. This method took into account the speed differential between vehicles. A reduction of speed differential could thus be used as an determinant of safety effectiveness of climbing lanes. Following much literature search, it was concluded that the most appropriate safety information/data available for climbing lane contexts are contained in papers by Glennon and the AASHTO manual for geometric design [3,10].

For the development of the microcomputer program, the relationship between safety and speed reduction upgrade was quantified. In the absence of sufficient number of data points for the development of functions, it was decided to use the graph contained in the AASHTO design manual. The shape of the graph suggests that it could be represented by two distinct segments that are nearly linear, although with different slopes. This reflects the phenomenon that the accident involvement rate increases rapidly above 15 km/h reduction in speed. This pattern of accident involvement rates has resulted in the 15 km/h speed

drop criterion for the consideration of a climbing lane.

In order to be able to use it in the microcomputer program, the graph was split into two linear components and equations were developed for those two components. These two regression equations (accident involvement estimation equations) are presented below.

For speed reduction of 0 to 15 km/h:

Accidents per 100 million vehicle km of travel =
132.441 + 22.085 (speed reduction in km/h)

$r^2 = 0.98$

For speed reduction of over 15 km/h:
Accidents per 100 million vehicle km of travel =
- 992.853 + 95.470 (speed reduction in km/h)

$r^2 = 0.99$

Example applications of accident involvement equations are presented in Table 5.1. Clearly, an increase in the magnitude of speed reduction results in a much higher rise in estimated accidents per 100 million-km of travel. A comparison of results with past statistics is shown below.

Speed Reduction km/h	Accident Involvement Rate (Glennon)	Estimated from Regression Equations
8	299	309
16	567	535
24	1362	1298

Another type of check can be made on the accident involvement rate as estimated by regression equations. For 0% reduction in speed (i.e., for level or rolling areas), the estimated number of accidents is 132.441 accidents/100 million vehicle-km or 1.32 accidents per million vehicle-kms. Recent safety data for Ontario, applicable to "King's Other Highways" (i.e., other than freeways) show the following trend [22].

Accidents per Million Vehicle-km:
(Highways Other than Freeways, Ontario)

1983: 1.0 1984: 1.1 1985: 1.2 1986: 1.1 1987: 1.1

Table 5.1

Example Applications of Accident Estimation Equations

Speed Reduction Km/hour	Accidents/100 Million Vehicle-km of Travel
0 km/h *	132
10 km/h *	353
20 km/h **	916
30 km/h **	1817

Notes: * Estimated from the equation noted below, applicable to speed reduction values of 0 to 15 km/h

Accidents/100 million veh.-km of travel = 132.441 + 22.085 (speed reduction in km/h)

** Estimated from the equation applicable to speed reductions more than 15 km/h

Accidents/100 million veh.-km of travel = - 992.853 + 95.470 (speed reduction in km/h)

Considering that "King's Other Highways" include 2 lane and multilane highways, accident rate for two lane highway would be somewhat higher than 1.1 accidents/million veh.-km of travel. Therefore, 1.32 accidents/million veh.-km obtained from the use of regression equation is a realistic estimate.

Finally, results obtained from regression equations can be checked against safety data from Sweden (reported in reference 17). These compare favourably. According to Swedish statistics, a reduction in accident rate of 1.75 accidents/per million vehicle-kms could be expected due to a climbing lane. An assumption is made that without a climbing lane the reduction in speed as compared to approach section, is 15 km/h and that speed reduction is only 5 km/h with a climbing lane. The drop in accident rate/million vehicle-km would be about 2.2. This answer compares favourably with 1.75 accidents/million veh-km, based on Swedish experience with climbing lanes.

Chapter 6

VERIFICATION OF OPERATIONAL PERFORMANCE ESTIMATION MODELS

6.1 Introduction

For the development models that are to be used to analyze operational performance of upgrade sections on two lane highways, the site characteristics (used as inputs to the TWOPAS model) and the corresponding outputs of the TWOPAS model were used. Site characteristics represent the traffic and geometric design features of the highway sections of interest. Also, specified are the average approach speed of traffic (a function of design speed and speed limit), and the degree of platooning at the approach to upgrade section. Guidelines are available from the TWOPAS model developers on appropriate platooning estimates that correspond to various volume levels.

Although the TWOPAS model has been tested extensively by other researchers for generally level and rolling terrain, its application for the specific grades has not been carried out. Therefore, it was considered appropriate to carry out field studies in order to collect data on the performance of upgrade sections on a two lane highway and to compare results with performance simulated by the regression equations as well as the TWOPAS model.

6.2 Choice of Sites

Since regression equations developed cover upgrade sections with and without climbing lanes, it was appropriate to include each type of site for field observations. Sites "with climbing lane" and "without climbing lanes" were identified for field data collection on the performance of upgrade sections of a two lane highway. Two such sites on Highway 17 were identified.

The site without a climbing lane is located on Highway 17 near the of Exit "Bruce Street, Renfrew, and Road 20". The northbound direction has a grade of 3% and has pavement markings prohibiting passing for most of its length. The approach to the upgrade section has a slight downgrade and no sight distance or other geometric design restrictions are present. The design speed for the approach section appears to be 100 km/h.

Main features of the site "without a climbing lane" are summarized below.

. Grade = 3%
. Length of section = 1300 m

. Volume = 875 vehicles /hour (for both directions)
. Directional split = 56% upgrade direction
. Trucks = 5%
. Recreational vehicles = 5%

The site with a climbing lane is also situated on Highway 17 -- south/east of Breezy Heights Road and south of Anterim truck stop. On its northbound direction, it has a grade of 3% and has a climbing/passing lane for northbound traffic. The auxiliary lane ends beyond crest. Passing is allowed along the entire length of the section of interest. The approach to the upgrade section has level grade and has no sight distance or other geometric design restrictions are present. The design speed for the approach section can be assumed to be 100 km/h.

Main features of the site "with a climbing lane" are noted below for ease of reference.

. Grade = 3%
. Length of section 1600 m
. Climbing lane length = 1000m
. Volume = 822 vehicles/hour (for both directions)
. Directional split = 63% (upgrade direction)
. Trucks = 8%
. Recreational vehicles = 6%

6.3 Field Study Methods

At the selected sites, measurements of spot speed and spot platooning were carried out. Radar meters were used to observe speed of vehicles at the downgrade and upgrade locations. A video camera enabled the observation of traffic volume and platooning. The videotape also proved to be useful for estimating average speed of vehicles. In addition to videotaping of traffic, manual counts were carried out as a back up measure. Each site was surveyed for one hour.

The use of radar meter readings enabled the estimation of spot speed down grade as well as upgrade. Average of these spot speeds (measured by radar meters) was used as one estimate of the average speed. The video tape was used to measure the extent of platooning (based on a headway of 4 seconds or less), the average speed of traffic within the length of road captured by the camera, the volume of traffic in each direction, and the composition of traffic.

6.4 Comparison of Models with Field Data

6.4.1 Performance Estimated From the Use of Regression Equations and TWOPAS Model

The regression equations developed in this study were used

to estimate the performance of upgrade sections. In addition to equations that give an estimate of average speed, equations for estimating percent of vehicles in platoons were also used.

Considering that the equation for estimating upgrade average speed was developed by using 90 km/h approach speed and that the approach speeds at sites surveyed were higher than 90 km/h and also that the approach sections were clear of any geometric design constraints, it is clear that the design speed for the approach sections is 100 km/h or even higher. The HCM (1985) recommends that a speed increment of about 6.5 km/h should be added to the estimates based on 90 km/h design speed.

In addition to the use of the regression (macrosimulation) models, the survey sites were simulated by using the TWOPAS model. Approach speeds of 90 km/h as well as 100 km/h were used.

6.4.2 Verification of Models: General

As the TWOPAS model has not been extensively tested against field data for specific upgrades, it was considered appropriate to test it in the present study. Also, the intent of this field study was to test the results of the regression equations against the field data. Although the methodology developed in this study does not require the use of TWOPAS model directly, the regression equations developed were calibrated with the TWOPAS outputs.

6.4.3 Site Without A Climbing Lane

In the case of the site without a climbing lane, the following traffic volume and composition data were observed.

	Upgrade Direction	Opposing Direction
Cars	444 veh/h	345 veh/h
Trucks	18	23
RVs	25	18
Total Volume	487	388

Two different observations of average speed became possible from field data. From the spot speeds measured at approach and upgrade, the average speed was inferred. Secondly, the videotape playback was used as a basis for developing an estimate of average speed. These observations are noted below. Also noted are observation on % of vehicles in platoons.

Table 6.1

Results of Field Study: Site Without Climbing Lane

Spot Speed		Average Speed Estimated from Spot Speeds	Average Speed Measured from Videotape	% of Vehicles in Platoons
Approach	Upgrade			
94.65 km/h	79.48 km/h	87.07 km/h	91.5 km/h	63%

The use of TWOPAS and regression models resulted in the answers shown in Table 6.2. The upgrade average speed estimates obtained from TWOPAS model simulations are close to those obtained from the regression model. For TWOPAS simulations that are based on 100 km/h approach speed, the average speed upgrade checks very well with results of regression models. The estimates of average speed obtained from TWOPAS and regression models, following the adjustment for design and approach speeds (if applicable), are close to that measured in the field. Also, model results for the two cases of overtaking regulations are logical.

The field result of % vehicles in platoons appears to be high, given that the grade is only 3% and that the two-way traffic volume is only 875 veh/h. The percent vehicles in platoons estimated by the regression and TWOPAS models are lower than the field survey result. The use of error of estimate puts the regression model result closer to field data. The reason for a higher than expected level of platooning is the presence of an exit located just beyond the survey station on the upgrade section. The bunching of traffic and reduced upgrade spot speed appear to relate to this feature of the highway.

6.4.4 Site With A Climbing Lane

Traffic volume and its composition for this site are summarized below.

	Upgrade Direction	Opposing Direction
Cars	444 veh/h	258 veh/h
Trucks	32	31
RVs	40	10
Total Volume	521	301

Table 6.2

Estimated Performance: Site Without A Climbing Lane
Results of TWOPAS & Regression Models

Upgrade Average Speed	Average Speed Adjusted for Design Speed*	% of Vehicles in Platoon
TWOPAS Model Simulations		
81.32 km/h (90 km/h approach speed & overtaking allowed)	87.37 km/h	52.0%
80.97 km/h (90 km/h approach speed & overtaking not allowed)	87.47 km/h	53.0%
90.14 km/h (100 km/h approach speed & overtaking allowed)	-	46.0%
89.97 km/h (100 km/h approach speed & overtaking not allowed)	-	47.0%
Regression Models		
79.87 km/h** (assumption of no overtaking)	86.37 km/h (assumption of no overtaking)	47.56%+ (assumption of no overtaking)

* The equations were based on the assumption of 90 km/h approach speed. Since the highway approach speed is 94.65 km/h and given that the design speed of the highway section preceding the upgrade section is 100 km/h, the HCM (1985) guidelines are used in the form of adding 6.5 km/h to average speed estimated by the regression equation.

** The range is defined by + & - 6.29 km/h.
+ The range is defined by + & - 10.69 %

Note: The above ranges are defined by the standard errors of estimate.

As in the case of the site without climbing lane, field observations for this site were made in the form of radar meter readings of speed and the videotaping of traffic. The first estimate of average speed is obtained from the averaging of the spot speeds measured at approach and upgrade locations of the roadway section. The second estimate is obtained from the videotape. The estimate of % vehicles in platoons was obtained from the videotape by using a headway criterion of 4 seconds or less.

Table 6.3

Results of Field Study: Site With A Climbing Lane

Spot Speed				
Approach	Upgrade	Average Speed Estimated from Spot Speeds	Average Speed Measured from Videotape	% of Vehicles in Platoons
96.71 km/h	93.7 km/h	94.89 km/h	93.12 km/h	47%

The average upgrade speed and % of vehicles in platoons were estimated from the use of regression equations. Also, the TWOPAS model was used to simulate the performance of this site. The results are shown in Table 6.4.

In the case of site with a climbing lane, the average speed as well as percent vehicles in platoons estimated from models match very well with field measurements. The results obtained from the regression models check very well with those of the TWOPAS model. This suggests that the macrosimulation models calibrated in the form of regression equations from the TWOPAS outputs provide answers that are similar to those obtainable from expensive microsimulations of sites of interest.

Table 6.4

Estimated Performance: Site With A Climbing Lane
Results of TWOPAS and Regression Models

Average Speed Upgrade	Average Speed Adjusted for Design Speed*	% of Vehicles in Platoons
TWOPAS Model Simulations		
83.31 km/h (90 km/h approach speed & overtaking allowed)	89.81 km/h	45.0%
83.03 km/h (90 km/h approach speed & overtaking not allowed)	89.53 km/h	45.0%
91.03 km/h (100 km/h approach speed & overtaking allowed)	-	45.0%
91.18 km/h (100 km/h approach speed & overtaking not allowed)	-	46.0%
Regression Models		
86.76 km/h* (Overtaking allowed)	93.26 km/h (overtaking allowed)	48.11%+ (overtaking allowed)
85.13 km/h** (overtaking not allowed)	91.26 km/h (overtaking not allowed)	47.98%++ (overtaking not allowed)

* 68% probability of having the answer within the range defined by + & - 5.05 km/h
** The range is defined by + & - 5.28 km/h
+ The range is defined by + & - 5.32 %
++ The range is defined by + & - 6.42 %

Chapter 7

COST-EFFECTIVENESS OF CLIMBING LANES

7.1 Introduction

The cost of providing a climbing lane should be viewed against the effectiveness of such a lane in improving the safety and operational efficiency of the two lane highway section under study [23,24,25,26]. The measures of effectiveness are to be defined and quantified. These are quantified in their different original units (e.g., minutes, accidents). The comparison of single measures of effectiveness against cost can be carried out with much ease. However, the investigation of multiple measures of effectiveness requires the use of a relative value approach to obtain a combined measure of effectiveness. Following the development of such measures, the cost-effectiveness of a climbing lane option could be investigated.

The economic feasibility of a climbing lane option could also be investigated, required the valuation of benefits. The application of the criterion of present value of net benefits may be applied, based on the estimation of discounted cash flow over the analysis period.

This chapter describes the methodology for conducting the cost-effectiveness studies as well as the economic feasibility of climbing lane options.

7.2 Effectiveness Measures

The effectiveness measures to be used include:
. reduction of delay (hours/year)
. reduction of accident involvement rate/100 million vehicle-km.

The methodology for the estimation of delay reduction attributed to a climbing lane has been discussed in Chapter 4. The number of hours of delay reduction per year could be calculated for various options under study. Also, for one climbing lane site, such estimates could be obtained for a number of traffic levels (e.g., design hourly volumes of 300 to 1500).

The subject of estimating the reduction of accidents was discussed in Chapter 5. The use of regression equations enables the quantification of the reduction of accident involvement rate per 100 million vehicle-km. As in the case of delay, accident reductions could be estimated for various alternatives. Also, such estimates could be defined for a given site under traffic

volumes that could be varied from low to a high number of vehicles/hour.

7.3 Multiple Measures of Effectiveness

Following the quantification of multiple measures of effectiveness, relative values have to be developed. The delay reduction DR and accident reduction AR are to be transformed into relative values. The procedure is described here and an example application can be found in Chapter 8.

For all alternatives under consideration, or for various traffic levels applicable to one alternative, identify the highest value of effectiveness measure. Set it equal to 1 (the highest value on the 0 to 1 scale). Find the remaining values by taking ratios -- e.g., set 5,288 hrs of delay reduction/year = 1. Then the relative value for 5,477 hours/year is = (1/5,288) x 2,739 = 0.52.

Weighting of effectiveness measures is to be carried out next. User-specified weights (W) can be assigned such that:

WDR + WAR = 1.0

Weighted effectiveness can now be found.
Weighted effectiveness of an alternative = (WDR)(DR) + (WAR)(AR).

7.4 Economic Feasibility of Climbing Lanes: Estimation of Benefits

For each alternative, or for different traffic levels for one alternative, the dollar value of benefits has to be estimated. A base year is to be defined by the analyst for the calculation of present value of benefits and costs. Benefit measures to be used are:

- delay reduction, and
- reduction in accident involvement rate.

For reconciling the profile of benefits and costs over time, a real rate of return i is to be specified. For benefit-cost analysis "without discounting" of benefits, i=0. Also, the inflation rate f is to be specified by the analyst.

Life of facility N, and therefore the period for analysis is to be defined. A 30 year period is suggested as the default value.

Other factors that have to be specified are:
- VT -- value of saving one vehicle-hour (VT) expressed as $/h in the constant dollar of the base year,

. VAC -- value of reducing one accident involvement, in constant dollar of base year.

7.4.1 Estimation of Benefits "Without Discounting"

Benefits of a climbing lane would occur over time. Since the values of VT and VAC are originally specified in the constant dollars of the base year, these could be expressed in the actual dollars of future years by using the inflation factor. As there is no intent to discount the future benefits (i.e., the real rate of return is specified to be equal to zero), the present value of benefits can be found by deflating the benefits at the rate of inflation f. The effects of inflating benefits and then deflating these cancel each other, resulting in constant dollars of the base year.

Benefits/year (in constant $ of base year) =

$$\sum_{n=1}^{N} \left(\frac{\text{(Delay reduction hr/yr)} \times VT(1+f)^n}{(1+f)^n} \right) \times (1/N) +$$

$$\sum_{n=1}^{N} \left(\frac{\text{Reduction in accident involvement/yr)} \times VAC(1+f)^n}{(1+f)^n} \right) \times (1/N)$$

= {(Delay reduction in hrs/yr)xVT) +
{(Reduction in accident involvement/yr) x VAC}

7.4.2 Estimation of Benefits "With Discounting"

The use of a real rate of return of i in the calculation of the present values of benefits implies that the present value of future benefits would be less than was the case when benefits were not discounted. The higher the magnitude of discount rate i (the real rate of return), the lower would be present value of future benefits.

The appropriate magnitude of the real rate of return for public projects is a management decision. The use of private sector interest rates over the rate of inflation is an option. However, the nature of benefits of highway investments (i.e., safety, delay reduction) suggests that commercial rates of return may not be appropriate. A value between i = 0 and i = prevailing market rate might be appropriate.

Benefits/year (in constant $ of base year) =

$$\sum_{n=1}^{N} \left\{ \frac{(\text{Delay reduction (hrs/yr)}) \times VT(1+f)^n}{(1+f)^n(1+i)^n} \right\} \times (1/n) +$$

$$\sum_{n=1}^{N} \left\{ \frac{(\text{Reduction in accident involvement/year}) \times VAC(1+f)^n}{(1+f)^n(1+i)^n} \right\} \times (1/N)$$

$$\sum_{n=1}^{N} \left\{ \frac{(\text{Reduction in accident involvement/year}) \times VAC(1+f)^n}{(1+f)^n(1+i)^n} \right\} \times (1/N)$$

$$= (\text{Delay reduction (hrs/yr)} \times VT)\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \times (1/N) +$$

$$(\text{Reduction in accident involvements/yr}) \times VAC \times \left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \times (1/N)$$

7.5 Cost of Climbing Lane

For each alternative to be analyzed, the following cost estimates are relevant for inclusion in cost-effectiveness and economic feasibility studies.

1. Construction cost of climbing lane/km in the constant dollar of base year,
2. Maintenance cost of climbing lane/km in the constant dollar of base year,

From the above two items, cost of a climbing lane alternative (in the constant $ of base year) can be estimated:

Cost/year = [(Length of climbing lane in km) x Cost/km] x (1/N)

7.6 Economic Feasibility

All the necessary information has now become available for the estimation of the economic feasibility of alternatives and for conducting sensitivity analyses. The procedure calls for the calculation of net benefits/year (in constant $ of base year).

Net benefits/year in the constant $ of base year
= [(Benefits/year in constant $) - (Cost/year in constant $)]

Sensitivity analyses could be carried out to observe the value of net benefits/year by making changes to i, cost, VT, VAC, and N.

7.7 Cost-Effectiveness of Alternatives

For each alternative or for various traffic levels for a given alternative, cost-effectiveness values could be studied in support of decision-making. Single measures of cost-effectiveness of the following types could be assessed:

. Vehicle-hours of delay reduction/$ of cost
. $ cost/veh-hr of delay reduction
. Accident involvement reduction/million dollar of cost
. $ cost/accident involvement reduction

As for the cost vs. overall effectiveness, plots of the index of overall effectiveness against cost could be examined in order to assess the relative desirability of climbing lane alternatives or the effectiveness of a given alternative against its cost.

Chapter 8

MICROCOMPUTER PROGRAM AND EXAMPLE APPLICATION

8.1 Program Logic

The methodological framework and its components described in Chapters 3 to 7 were used as the basis for the development of a microcomputer program, namely Cost Effectiveness of Climbing Lanes (CECL). A User's Manual and a Programmer's Manual describe the program. Here, the intent is to describe the program logic and to show example applications.

The overall program is designed to consist of a number of modules. The modular format offers much flexibility to the user for applications in climbing lane planning, analysis and evaluation (Figure 8.1). The overall program consists of modules A to G (although not identified in the user's and programmer's manuals as such).

8.1.1 Module A

Module A deals with inputs in terms of roadway and traffic characteristics. The following are the information items and their format.

- Grades, length of grades
- Passing allowed/passing not allowed
- Traffic volume:
  Design hour volume (DHV)
  Average Annual Daily Traffic (AADT)
- Directional split:
  Uphill direction = Direction 1
  Downhill direction = Direction 2
- Percent trucks
- Percent recreational vehicles (RVs)
- Peak Hour Factor (PHF)

The program is designed to compute all required information for a number of traffic levels for a given site. The DHV levels that are included in the list for sensitivity testing are: 300, 500, 1000, and 1500. Also corresponding AADTs are used as well.

The program accepts inputs for one candidate site for one cycle of program use. Multiple sites should be handled separately and results could be compared.

Grades could be specified in a variety of fashion, depending upon terrain. Positive grade(s) are to be checked in order to

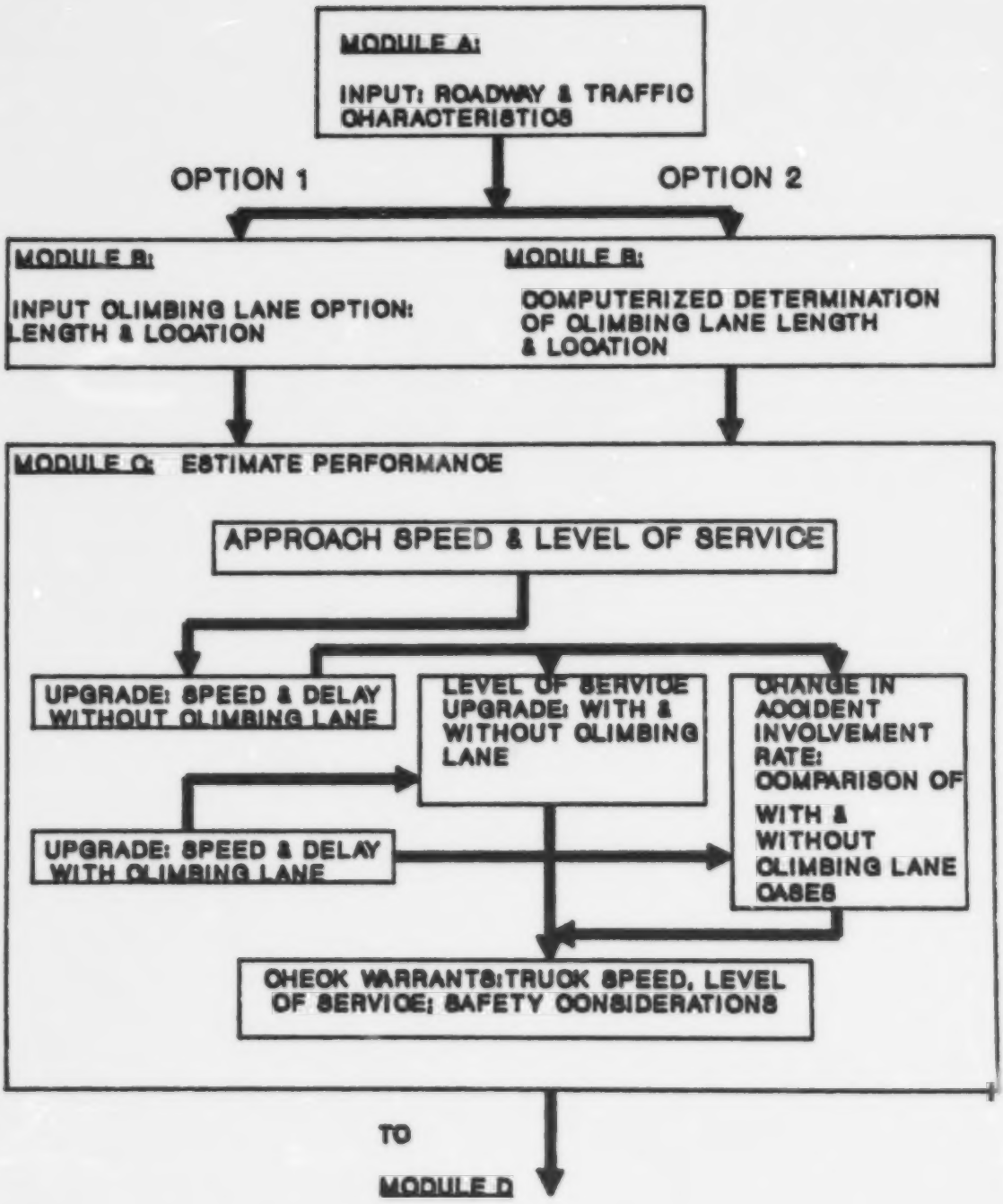

MODULE A:
INPUT: ROADWAY & TRAFFIC CHARACTERISTICS
OPTION 1
OPTION 2
MODULE B:
INPUT CLIMBING LANE OPTION: LENGTH & LOCATION
MODULE B:
COMPUTERIZED DETERMINATION OF CLIMBING LANE LENGTH & LOCATION
MODULE C: ESTIMATE PERFORMANCE
APPROACH SPEED & LEVEL OF SERVICE
UPGRADE: SPEED & DELAY WITHOUT CLIMBING LANE
LEVEL OF SERVICE UPGRADE: WITH & WITHOUT CLIMBING LANE
CHANGE IN ACCIDENT INVOLVEMENT RATE: COMPARISON OF WITH & WITHOUT CLIMBING LANE CASES
UPGRADE: SPEED & DELAY WITH CLIMBING LANE
CHECK WARRANTS: TRUCK SPEED, LEVEL OF SERVICE; SAFETY CONSIDERATIONS
TO
MODULE D

Figure 8.1: Logic Diagram for Microcomputer Program (CECL)

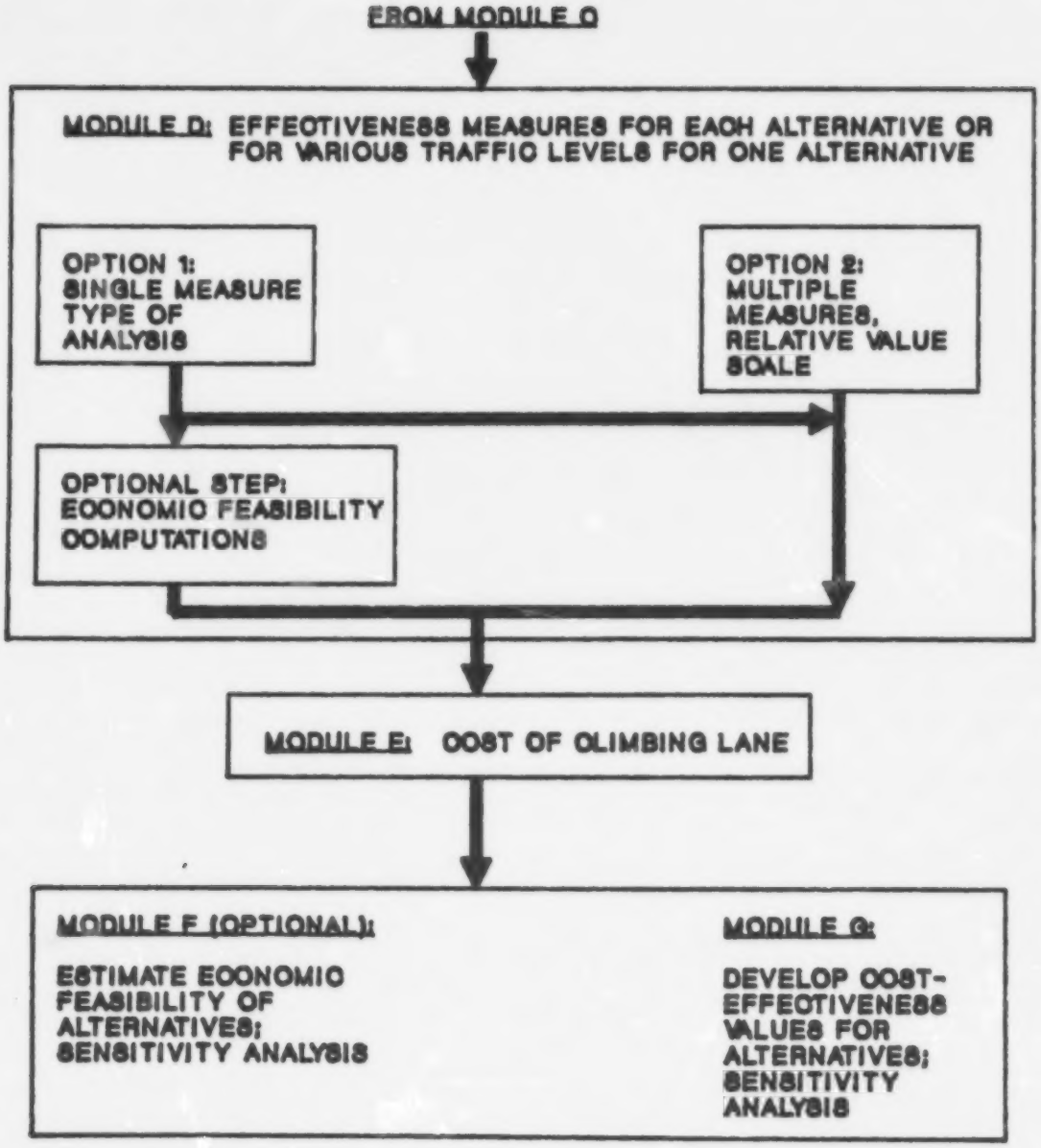

FROM MODULE O
MODULE D: EFFECTIVENESS MEASURES FOR EACH ALTERNATIVE OR FOR VARIOUS TRAFFIC LEVELS FOR ONE ALTERNATIVE
OPTION 1: SINGLE MEASURE TYPE OF ANALYSIS
OPTION 2: MULTIPLE MEASURES, RELATIVE VALUE SCALE
OPTIONAL STEP: ECONOMIC FEASIBILITY COMPUTATIONS
MODULE E: COST OF CLIMBING LANE
MODULE F (OPTIONAL):
ESTIMATE ECONOMIC FEASIBILITY OF ALTERNATIVES; SENSITIVITY ANALYSIS
MODULE G:
DEVELOP COST-EFFECTIVENESS VALUES FOR ALTERNATIVES; SENSITIVITY ANALYSIS

Figure 8.1: Logic Diagram for Microcomputer Program (CECL) (Continued)

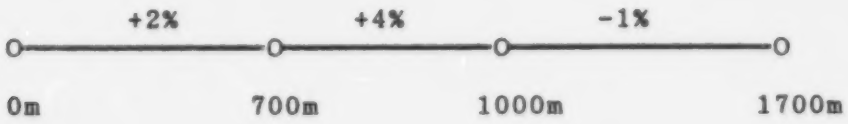
establish whether to use:

. average grade (for composite positive grades), or
. individual grade.

Guidelines for the choice of method are based on HCM (1985). If no single grade exceeds 4% or total length of composite (positive) grade does not exceed 1220m, average grade may be used for the study of truck speed drop upgrade.

Example 1:

Here, use average grade:



Total rise = 700x2 + 300x0.04 = 26m
Average (up) grade = (26/1000)x100 = 2.6%

Example 2:

In the case noted below, use 7% as the upgrade up to 1000m distance.

Passing (overtaking) information is to be specified in terms of:
. overtaking allowed (i.e., 0% no passing zones)
. overtaking not allowed (i.e., 100% no passing zones).

Intermediate values of "percent no passing zones" may also be specified.

The DHV is specified as a percent of AADT. For example, DHV = 19.4% of AADT.

Traffic composition has to be provided as an input to the program. Percent trucks and % RVs are to be provided by the user.

Heavy truck selection is permitted. Two options are 180 kg/kw and 120 kg/kw.

8.1.2 Module B

Module B has two functions. In one case, a computerized determination of climbing lane length and location could be carried out. The program offers the choice of truck type (180 kg/kw and 120 kg/kw). The automated determination of climbing lane geometry is based on the criterion of a 15 km/h speed drop for starting a climbing lane and ending the climbing lane beyond crest where the design truck regains speed such that its speed is within 15km/h difference.

The approach speed for the heavy truck is assumed to be 90 km/h for climbing lane design. It should be noted that under high volume conditions, approach speed of 90 km/h may be difficult to attain (at 0% grade). On the other hand, under very low traffic and very favourable sight distance conditions, a truck of 120 kg/kw may attain approach speeds of 100 km/h. Even the 180 kg/kw truck can attain 93.8 km/h speed on level grade. Here, the intent is not to find various lengths of climbing lanes that correspond to different approach speeds. In order to reduce the number of climbing lane lengths to be analyzed, it is assumed that the heavy truck selected will enter the upgrade section at the posted speed of 90 km/h.

The computer program estimates the speed of heavy truck at various locations along the positive grade. For example, for a single grade, it uses the speed-distance tables (curves) that yield "deceleration upgrade". Speed at crest is found first. Next, this speed is used by the program as the starting point for the use of table (curve) marked "acceleration on level road or downgrade. The computer program finds the location where the speed of truck drops 15 km/h below the highway speed (i.e., 75 km/h) and that location where the truck regains speed to the 75 km/h level. These locations are the beginning and the ending points of the truck climbing lane.

The length of climbing lane is approximated by tangents rather than the length of vertical curves. Transition distance is in part included in the estimation of climbing lane. If the estimated climbing lane is less than 1500m, a length of 1500m is used (including transition distance.

In the second option, the user may wish to specify the geometric features of the climbing lane. For a number of reasons, such as topography, a designer may wish to deviate from the above noted procedure which results in taking the climbing lane beyond crest. The analyst may start the climbing lane at the beginning of the upgrade section and end it near the crest or at crest.

The computer program requires inputs on the starting and ending points of the climbing lane.

8.1.3 Module C

Module C is devoted to the estimation of climbing lane performance in terms of level of service and speed. The information generated by this module enables the checking of warrants in terms of truck climbing performance and level of service drop. Accident reduction information is also displayed.

For the estimation of approach speed and level of service (LOS), the assumption of 100 km/h design speed is made. However, 90 km/h design speed could also be assumed since the program has built-in guides applicable to both design speed levels. This part of Module C uses the HCM (1985) procedures for level terrain. The methodology for such calculations has already been discussed in Chapter 4.

8.1.4 Module D

Module D is devoted to the estimation of effectiveness measures for each alternative. Two different types of effectiveness studies can be carried out. Single measures of effectiveness can be quantified for a number of alternatives or for various traffic levels for one site. The effectiveness measures used are: reduction in delay and reduction in accident involvement rate.

8.1.5 Modules E, F & G

Module E is devoted to the calculation of cost of climbing lane. Module F is intended to carry out computations for assessing the economic feasibility of alternatives and sensitivity tests. Module G deals with the cost-effectiveness of alternatives and sensitivity analysis. Theoretical aspects of these methods for evaluation of climbing lane alternatives have been covered in Chapter 4. An example application included in this chapter provides details of computational steps involved.

8.2 Example Application

A rural segment of a two lane highway has a 1 km long 7% grade, preceded by as well as followed by level terrain. Check the fulfillment of warrants for a climbing lane. Also, study the cost-effectiveness as well as economic feasibility of a climbing lane for DHV levels that range from 300 to 1500. Percent traffic in the upgrade direction is 50%. Percent trucks and % RVs are each equal to 10%. Use a PHF of 1.0. Estimate performance under the assumption of overtaking allowed. Also show selected answers

for overtaking not allowed. The weight/power ratio of the design truck is 180 kg/kw.

This example was solved manually and also by the use of the microcomputer program. Here, both outputs are displayed. Due to different levels of significant figures and rounding, answers at times are somewhat different.

8.2.1 Inputs, Climbing Lane length and Location

The roadway and heavy truck data were used to manually estimate the length and location of climbing lane. A climbing lane of about 2000m is required, starting 200m from the beginning of upgrade section.

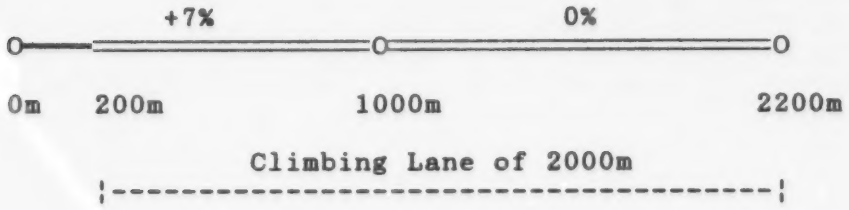


Table 8.1 is the screen dump from Module A of the CECL showing roadway and traffic input characteristics. Table 8.2 shows the results of the computerized technique for determining climbing lane length and location. The starting point for the climbing lane is 149m and the length is 2014m.

8.2.2 Estimation of Performance (Module C)

Approach Speed & Level of Service: "Overtaking Allowed"

The methodology for Module C is used as a basis for the estimation of various indicators of performance for the roadway under study.

Example:

Average approach speed = 90 km/h
$(v/c)_s$ = 0.27 for LOS B (Table 4.1)
f_d = 1.0 (Table 4.2)
f_w = 1.0 (Table 4.3)

Table 8.1

Roadway and Traffic Inputs

Roadway and Traffic Characteristics

Site ID: **example1** Description: **Example from draft, Work Items 7 & 8**

GRADES

Distance, m	Grade, %
0	
	7.0
1000	
	0.0
3000	
	0.0
0	
	0.0
0	

TRAFFIC VOLUME

DHV % of AADT 17.4 %

Case	1	2	3	4
DHV, v/hr	300	500	1000	1500

% Uphill 50.0 %

% Trucks 10.0 %

% RV's 10.0 %

Peak H.F. 1.0

TRUCKS

Truck Weight: 180 kg/kw

PASSING ZONES

Passing allowed ? **Yes**

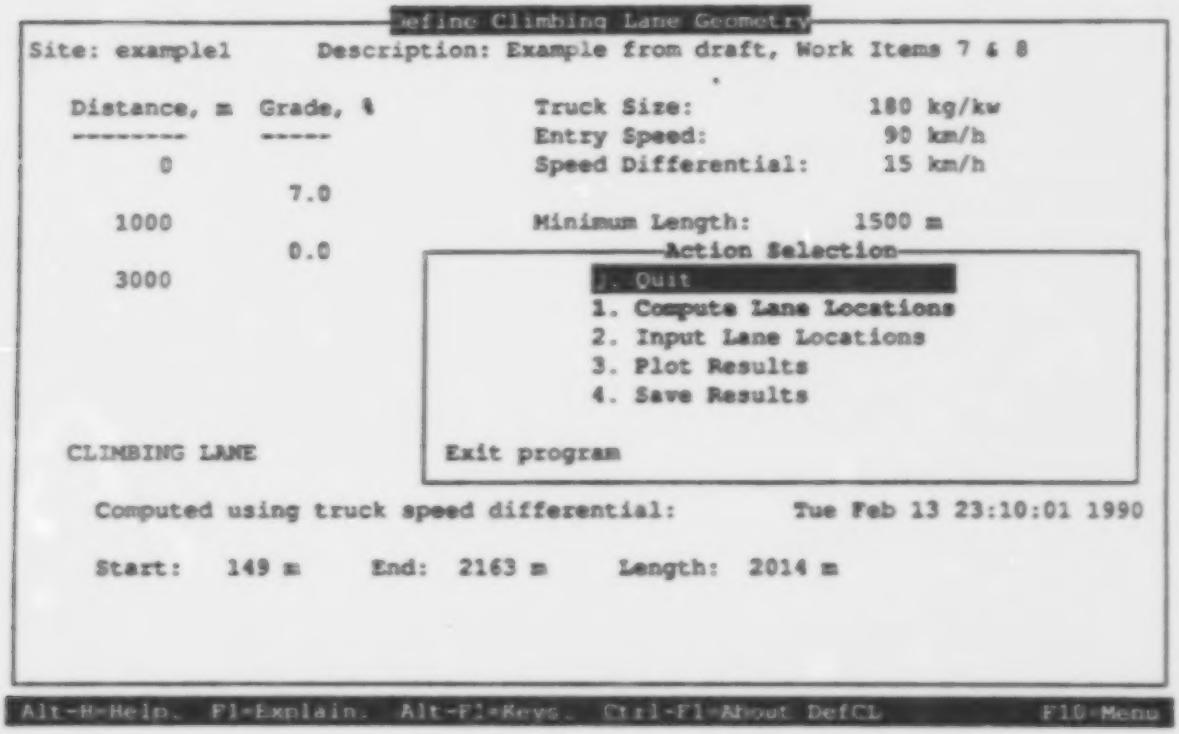
Percent no-passing zones ? **0.0 %**

Save ? No Yes

Alt-H=Help. F1=Explain. Alt-F1=Keys. Ctrl-F1=About DefSite F10=Menu

Table 8.2

Determination of Climbing Lane length



E_T = 2.2 (Table 4.4, LOB B)
E_R = 2.5 (Table 4.4, LOS B)
P_T & P_R = 0.1 (given)
f_{HV}(LOS B) = 0.79 (Equation noted in Chapter 4)
SF_{Loss} = 597 vph (Equation noted in Chapter 4)

The answers for various speeds & LOS are shown below.

Avg. Approach Speed (km/h)	93.4	90	84	80	72
LOS	A	B	C	D	E
SF (veh/h)	344	597	951	1541	2408

For given DHVs, find approach speed first, by taking into account the effect of peaking within the hour.

Two-way volume/h = DHV/PHF
For PHF =1.0, the DHVs are equal to volume estimates.

Approach speed is estimated by comparing volume with service flows (SFs) found earlier. Interpolation may be required. For example, for 300 veh/h, use 93.4 km/h and for 500 veh/h, interpolate.

Overtaking Allowed (0% no passing zones)

DHV	300	500	1000	1500
Approach Speed (km/h)	93.4	91.3	83.7	80.3
LOS (design speed 100 km/h) (From Table 4.1)	A	B	D	D
LOS (design speed of 90 km/h) (See footnote to Table 4.1)	A	A	B	C
LOS (use of upgrade speed and LOS criteria, Table 4.5)*	A	A	B	B

* Note: These are used in the program for approach LOS.

The reader may wish to note that in the estimation of level of service as illustrated above, for higher DHVs (e.g., 1500), the use of upgrade section LOS criteria shows a better LOS (i.e., C) than those obtained from the use of level grade criteria (i.e., D for 100 km/h design speed). This serves to illustrate the inconsistency in the guidelines provided in Chapter 8 of HCM (1985). Similar observations were made by other authors [27]. Conceptually, a highway cannot have a better LOS upgrade than level approach.

Approach Speed & LOS: Overtaking Not Allowed (100% No Passing Zones)

Example:
Average speed = 90 km/h: $(v/c)_s$ = 0.16
f_d = 1.0
f_w = 1.0
E_T = 2.2 (for LOS B)
E_R = 2.5 (for LOS B)
P_T & P_R = 0.1
f_{HV} (LOS B) = 0.79
SF_{Ross} = 354 vph

Approach Speed* (km/h)	>93.4	>90	>84	>80	>72
LOS	A	B	C	D	E
SF (veh/h)	92	354	708	1372	2408

* Based on design speed of 100 km/h.

As in the case of overtaking allowed, we can find approach speed and LOS for various DHVs. However, these computations were not carried out.

Upgrade Speed & Delay "Without Climbing Lane"

From the use of relations and tabular information presented in Chapter 4, various indicators of operational efficiency are found for a 1000m long upgrade section with a +7% grade. Intermediate steps are shown here as well, when relevant.

Speed (km/h)	90	85	80	72	64	48
E (found by interpolation)	11.04	7.32	5.20	3.72	3.13	2.69

P_0 = 0.8 (given)
P_{HV} = P_T + P_R = 0.1 + 0.1 = 0.2
$P_{T/HV}$ = P_T/P_{HV} = (0.1/0.2) = 0.5

$I_P = 0.02(E-E_0)$
$f_g = 1/[1 + P_P I_P]$; $P_P = 0.8$
$E_{av} = 1 + (0.25+P_{T/av})(E-1)$; $P_{T/av} = 0.5$
$f_{av} = 1/[1+P_{av}(E_{av}-1)]$; $P_{av} = 0.2$

Speed (km/h)	90	85	80	72	64	48
I_P	0.179	0.110	0.072	0.046	0.037	0.028
f_g	0.87	0.92	0.95	0.96	0.97	0.98
E_{av}	8.53	5.74	4.15	3.04	2.60	2.27
f_{av}	0.40	0.51	0.61	0.71	0.76	0.80

Next, compute total two-way service flow rates for designated speeds.

Overtaking Allowed (0% No Passing Zones)

Speed	2,800 x	v/c	x	f d x	f_w	x	f_g	x	f_{hv}	=	SF
90		0		1.0	1.0		0.87		0.40		0
85		0.13		1.0	1.0		0.92		0.51		171
80		0.34		1.0	1.0		0.95		0.61		552
72		0.77		1.0	1.0		0.96		0.71		1470
64		0.93		1.0	1.0		0.97		0.76		1920
48		1.00		1.0	1.0		0.98		0.80		2195

Overtaking Not Allowed (100% No Passing Zones)

90		0		1.0	1.0		0.87		0.40		0
85		0.04		1.0	1.0		0.92		0.51		53
80		0.12		1.0	1.0		0.95		0.61		195
72		0.35		1.0	1.0		0.96		0.71		668
64		0.59		1.0	1.0		0.97		0.76		1218
48		0.86		1.0	1.0		0.98		0.80		1880

Now we can find speed & LOS that correspond to DHVs of interest. Interpolations can be carried out to find speed for given DHVs.

The procedure to be used is as follows. For DHV values, find corresponding volumes by taking into account the PHF (i.e., volume = DHV/PHF). Next compare the resulting volumes with the SF as shown above. Interpolate if necessary and infer the speed. From speed, LOS can be inferred.

DHV	Volume for Comparison Purposes (veh/h)	Upgrade Speed (km/h)	LOS*
Overtaking Allowed, Without Climbing Lane (0% No Passing Zones)			
300	DHV/PHF = 300/1.0+ = 300	83.3	B
500	500/1.0 = 500	80.5	B
1000	1000/1.0 = 1000	76.1	C
1500	1500/1.0 = 1500	71.5	D
Overtaking Not Allowed, Without Climbing Lane (100% No Passing Zones)			
300	300	78.2	C
500	500	74.8	C
1000	1000	67.2	D
1500	1500	57.3	E

* LOS Criteria for Specific Grades + PHF = 1.0

LOS	A	B	C	D	E
Average Upgrade Speed (Km/h)	>90	80-89	72-79	64-71	<64 & >40

Note: HCM (1985) does not specify whether these apply to highways with 90 km/h design speed or 100 km/h of design speed or both.

Upgrade Speed "With Climbing Lane"

The case of climbing lane ending beyond crest is to be pursued here.

DHV vph	Upgrade Avg. Speed: Without Climbing Lane* km/h	Upgrade Avg. Speed: With Climbing Lane* km/h	Change in Upgrade Avg. Speed* km/h	Upgrade Avg. Speed Without Climbing Lane+ km/h
300	70.8	86.2	15.4	83.3
500	67.6	84.2	16.6	80.5
1000	59.6	79.1	19.5	76.1
1500	51.6	74.0	22.4	71.5

* Use of regression equations
+ HCM (1985) procedure as described above.

Estimation of Upgrade Average Speed.

DHV vph	Approach Speed km/h	Avg. Upgrade Speed Without Climbing Lane* km/h	Estimated Increase in Speed Due to Climbing Lane km/h	Estimated Upgrade Avg. Speed With Climbing Lane	
				Trial 1 km/h	Final trial+ km/h
300	93.4	83.3	15.4	98.7	89.0
500	91.3	80.5	16.6	97.1	89.0
1000	83.7	76.1	19.5	95.6	83.7
1500	80.3	71.5	22.4	93.9	80.3

* Use of HCM (1985) procedures as described above.
+ See Figure 4.2.

Display of Answers: Overtaking Allowed.

DHV	Approach Speed & LOS		Avg. Upgrade Speed & LOS Without Climbing Lane		Avg. Upgrade Speed & LOS With Climbing Lane	
vph	km/h	LOS	Km/h	LOS	Km/h	LOS
300	93.4	A	83.3	B	89.0	B
500	91.3	A	80.5	B	89.0	B
1000	83.7	B	76.1	C	83.7	B
1500	80.3	B	71.5	D	80.3	B

Delay associated with each case was calculated and reduction in delay due to climbing lane was estimated. Results are presented in a tabular form on the following page.

DHV	300	500	1000	1500
AADT	1724	2874	5747	8621
No Climbing Lane, Overtaking Allowed				
Approach Speed (km/h)	93.4	91.3	83.7	80.3
Upgrade Avg. Speed (km/h)	83.3	80.5	76.1	71.5
Delay/veh. (sec)	10.3	11.6	9.4	12.1
Total Delay/Yr. (Hrs.)	900	1690	2739	5288
With Climbing Lane, Overtaking Allowed				
Upgrade Avg. Speed (km/h)	89.0	89.0	83.7	80.3
Delay/veh (sec)	4.2*	2.2*	0*	0*
Total Delay/Yr. (Hrs)	367	321	0	0
Reduction in Delay/Yr (Hrs)	533	1369	2739	5288

* The trend and these numbers reflect approach speed & upgrade avg. speed.

Summary of Level of Service Computations
(Required for checking warrants for the provision of a climbing lane)

DHV	300	500	1000	1500
AADT	1724	2874	5747	8621
Approach LOS	A	A	B	B
Upgrade LOS Without Climbing Lane	B	B	C	D
Upgrade LOS With Climbing Lane	B	B	B	B

Accident reduction estimates can now be developed that are attributable to the presence of a climbing lane.

Reduction in Accident Involvement Rate				
DHV	300	500	1000	1500
AADT	1724	2874	5747	8621
Approach Speed (km/h)	93.4	91.3	83.7	80.3
Upgrade Operating Speed Without Climbing Lane (km/h)	83.3	80.5	76.1	71.5
Speed Reduction Upgrade Without Climbing Lane (km/h)	10.1	10.8	7.6	8.8
Accident Involvement Rate Without Climbing Lane (Acc./100m veh-km)	355.50	370.96	300.29	326.79
Upgrade Operating Speed With Climbing Lane (km/h)	89.0	89.0	83.7	80.3
Speed Reduction With Climbing Lane (km/h)	4.4	2.3	0	0
Accident Involvement Rate With Climbing Lane (Acc./100m veh-km)	229.62	183.24	132.44	132.44
Reduction in Accident Involvement Rate (Acc./100m veh-km)	125.88	187.72	167.85	194.35

Accident reduction per year is to estimated for cost-effectiveness study.

Roadway length = 2.2 kms (from the approach to the end of climbing lane)				
DHV	300	500	100	1500
AADT	1724	2874	5747	8621
Million Veh-km/Yr	1.38	2.31	4.61	6.92
Accident Involvements/ Yr. Without Climbing Lane	4.9	8.6	13.8	22.6
Accident Involvements/ Yr. With Climbing Lane	3.2	4.2	6.1	9.2
Reduction in Accident Involvements/ Year	1.7	4.4	7.7	13.4

Note: For "Other King's" Highways, in 1987

- one fatality for 52.82 accidents
- one injury for every 1.44 accidents
- average of $5,000/accident for "property damage"

Source for accident statistics: Reference [22].

Warrants for the provision of a climbing lane can now be checked.

Climbing Lane Warrants
Case: Overtaking Allowed

DHV	300	500	1000	1500
AADT	1724	2874	5747	8620
Heavy Truck Speed Reduction > 15 km/h*	Yes	Yes	Yes	Yes
Drop in LOS Upgrade+	No	No	Yes	Yes

* For increased safety and avoiding unreasonable delays caused by heavy vehicle performance on grade, the speed reduction criterion is 15 km/h (applies to heavy truck).

+ Whenever there is a drop of one or more levels of service upgrade vs. the design LOS of B for the highway, a climbing lane should be considered for that site.

Note that safety warrants are not defined directly. However, in an indirect manner, safety is included in heavy truck speed reduction criterion.

At this stage in describing the case study, it would be useful to show outputs from the CECL program. Table 8.3 shows user-specified climbing lane geometry. Table 8.4 is a screen dump summarizing performance estimates and results of a check on warrants. Table 8.5 is optional printout for the performance estimation module. The results of computer program are close to those obtained from manual calculations. As noted previously, the differences are due to rounding and the number of significant digits used.

8.2.3 Cost-Effectiveness and Economic Feasibility (Modules D-G)

The effectiveness of the climbing lane case is to be investigated for DHVs of 300, 500, 1000, and 1500. Initially, single measures are to be examined. Multiple measures are studied jointly. Economic feasibility of a climbing lane section in benefit-cost terms and the cost-effectiveness of the climbing lane are investigated. Estimates of performance indicators are based on the assumption that overtaking is allowed.

Table 8.3

User-Specified Climbing Lane Geometry

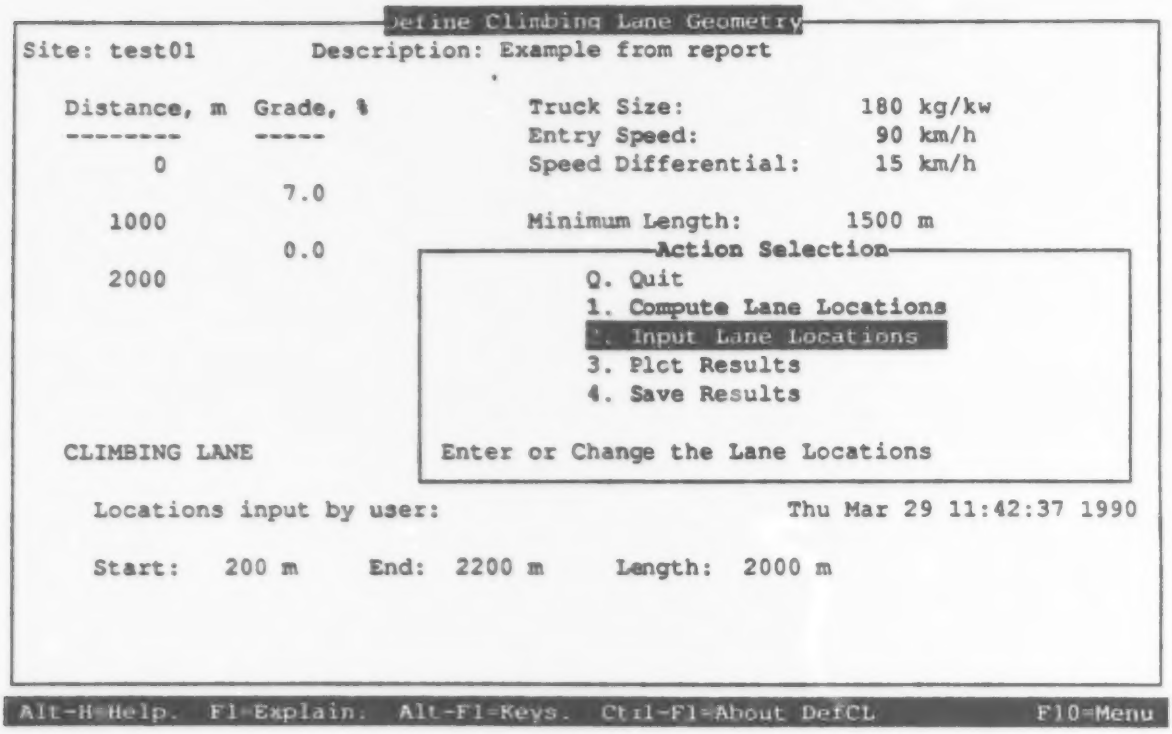


Table 8.4

Climbing Lane Performance Estimates

CECL 1.12 - Estimate Performance

Thu Aug 16 11:23:49 1990

Site: test01 - Example from report

Design Speed: **100** km/h
Lane Width: **3.66m**
Shoulder Width: **>= 1.83m**

DHV	300	500	1000	1500	veh/h
Approach	93.4 A	91.3 A	83.7 B	80.3 B	km/h LOS
Up Avg NoCL	83.3 B	80.7 B	76.1 C	71.6 D	km/h LOS
With CL	89.0 B	89.0 B	83.7 B	80.3 B	km/h LOS
Delay Red.	530.7	1335.4	2728.2	5245.9	hrs/yr
Acc. Red.	1.7	4.2	7.7	13.3	accidents/yr
TRUCK WARRANT	Yes	Yes	Yes	Yes	
LOS WARRANT	No	No	Yes	Yes	

'Yes' means that a climbing lane is required.

Note: Delay Reductions are for upgrade traffic only (50% of total)

Alt-H=Help. F1=Explain. Alt-F1=Keys. Ctrl-F1=About EstPerf F10=Menu

Table 8.5

Climbing Lane Performance Estimates: Optional Printout

```
CLIMBING LANE PERFORMANCE ESTIMATE        Thu Aug 16 11:23:49 1990
==================================

Site: test01      Description: Example from report

  Distance, m  Grade, %
  --------     -----
       0.0
                  7.0
    1000.0
                  0.0
    2000.0

  Average grade from 0 m to 1000 m = 7.00 %

  Lane Start: 200       End: 2200 m
  Highway Design Speed:      100 km/h
  Max. Vehicle Speed:         90 km/h
  Truck Weight:              180 kg/kw
  Percent No Passing Zones:    0
  Percent Upgrade:          50.0
  Percent Trucks:           10.0
  Percent RVs:              10.0
  DHV is                    17.4 % of AADT

     DHV  PHF  VPH
     ---  ---  ---
     300 1.00  300
     500 1.00  500
    1000 1.00 1000
    1500 1.00 1500


Approach Speed and LOS
**********************

Passing allowed (0% no-passing zones)
% Upgrade = 50.0,  % Trucks = 10.0,  % RV's = 10.0
Design Speed = 100 km/h
Lane width 3.66m,  Shoulder width >= 1.83m

 i LOS    AS    Et    Er   v/c    fd    fw   fhv    SF
 0   A  93.4  2.00  2.20  0.15  1.00  1.00  0.82   344
 1   B  90.0  2.20  2.50  0.27  1.00  1.00  0.79   595
 2   C  84.0  2.20  2.50  0.43  1.00  1.00  0.79   948
 3   D  80.0  2.00  1.60  0.64  1.00  1.00  0.86  1545
 4   E  72.0  2.00  1.60  1.00  1.00  1.00  0.86  2414

Approach Speed and LOS for the various DHV's:

   VPH    AS   LOS
   300  93.4     A
   500  91.3     A
  1000  83.7     B
  1500  80.3     B
```

Table 8.5 (Cont.)

Climbing Lane Performance Estimates: Optional Printout

Upgrade Speed and LOS without Climbing Lane
****

Grade 7.0 % from 0 m to 1000 m, length = 1.00 km
Proportion passenger cars, Pp = 0.80
Proportion heavy vehicles, Phv = 0.20
Proportion of trucks amoung heavy vehicles, Pt/hv = 0.50
% Upgrade = 50.0, fd = 1.00

i	LOS	AUS	E	E0	Ip	Ehv	v/c	fd	fw	fg	fhv	SF
0	A	90.0	11.03	2.10	0.179	8.53	0.00	1.00	1.00	0.87	0.40	0
1	B	85.0	7.32	1.80	0.110	5.74	0.13	1.00	1.00	0.92	0.51	172
2	B	80.0	5.20	1.60	0.072	4.15	0.34	1.00	1.00	0.95	0.61	552
3	C	72.0	3.72	1.40	0.046	3.04	0.77	1.00	1.00	0.96	0.71	1476
4	D	68.0	3.42	1.35	0.042	2.82	0.86	1.00	1.00	0.97	0.73	1709
5	D	64.0	3.13	1.30	0.037	2.60	0.93	1.00	1.00	0.97	0.76	1918
6	E	56.0	2.91	1.30	0.032	2.43	1.00	1.00	1.00	0.97	0.78	2123
7	E	48.0	2.68	1.30	0.028	2.26	1.00	1.00	1.00	0.98	0.80	2187

Upgrade Speed and LOS for the various DHV's:

VPH	US	LOS
300	83.3	B
500	80.7	B
1000	76.1	C
1500	71.6	D

Upgrade Speed and LOS with Climbing Lane
****

Grade 7.0 % from 0 m to 1000 m, length = 1000 m
Climbing lane from 200 m to 2200 m, length = 2000 m
Climbing lane ends beyond crest.
% Upgrade = 50.0, % Trucks = 10.0, % RV's = 10.0
Passing allowed (0% no-passing zones)

	Without C.L.			With C.L.			
vph	s0	s100	ssu	s0	s100	ssu	ssu inc
300	70.8	68.7	70.8	86.2	85.3	86.2	15.5
500	67.6	65.5	67.6	84.2	83.5	84.2	16.6
1000	59.6	57.5	59.6	79.1	79.0	79.1	19.5
1500	51.6	49.5	51.6	74.0	74.4	74.0	22.5

Average Upgrade Speed (AUS) for the various DHV's:

VPH	AS	US	SI	AUS	LOS
300	93.4	83.3	15.5	89.0	B
500	91.3	80.7	16.6	89.0	B
1000	83.7	76.1	19.5	83.7	B
1500	80.3	71.6	22.5	80.3	B

Table 8.5 (Cont.)

Climbing Lane Performance Estimates: Optional Printout

Delay Reductions Upgrade:
****

Distance = 2.2 km

DHV v/hr	VPH v/hr	NoCL km/h	CL km/h	VTR s/v	AADT v/d	TDR hr/y
300	300	83.3	89.0	6.07	1724	530.7
500	500	80.7	89.0	9.17	2874	1335.4
1000	1000	76.1	83.7	9.36	5747	2728.2
1500	1500	71.6	80.3	12.00	8621	5245.9

Change in Accident Involvments:
****

Distance = 2.20 km

		/------ No Lane -------\			/---- With Lane -----\			AI
VPH	AADT	SR	AIR	AI	SR	AIR	AI	RED.
300	1724	10.1	355.2	4.9	4.4	229.6	3.2	1.7
500	2874	10.6	366.6	8.5	2.3	183.0	4.2	4.2
1000	5747	7.5	298.7	13.8	0.0	132.4	6.1	7.7
1500	8621	8.7	324.9	22.5	0.0	132.4	9.2	13.3

Reduction in Delay (hrs/yr)

DHV	300	500	1000	1500
Reduction in Delay/Yr (hrs/yr)	533	1369	2739	5288
Delay Reduction minutes/ 100 vehicles	5.1	7.9	7.9	10.1

Reduction in Accident Involvement Rate (acc./100m veh-km)

DHV	300	500	1000	1500
Reduction in Accident Involvement Rate (Acc. per 100m veh-km)	125.88	187.72	167.85	194.35

The study of multiple measures of effectiveness requires the development of relative values. The measures are delay reduction (DR) and accident reduction (AR).

DHV	300	500	1000	1500
DR (hrs/yr)	533	1369	2739	5288
Relative Value for DR	0.10	0.26	0.52	1.00
AR (acc/yr)	1.7	4.4	7.7	13.4
Relative Value for AR	0.13	o.33	0.57	1.00

Example: Set the highest value of DR = 1 (on the scale of 0 to 1). Find the relative value of other DR estimates by taking ratios.
DR of 5288 = 1
DR of 5477 = (1/5288) x 2739 = 0.52

Weighting of effectiveness measures (user specified):

DR Delay reduction	Weight (w) =	0.4
AR Accident Reduction	Weight (w) =	0.6
		1.0

Weighted effectiveness:

DHV	Weighted Effectiveness
300	(W_{DR})(relative value for DR) + (W_{AR})(relative value for AR) = (0.4)(0.10) + (0.6)(0.13) = 0.12
500	(0.4)(0.26) + (0.6)(0.33) = 0.30
1000	(0.4)(0.52) + (0.6)(0.57) = 0.55
1500	(0.4)(1.00) + (0.6)(1.00) = 1.00

Economic feasibility study computations are described next. Benefit measures are DR and AR.

Base year = 1989
Real rate of return i = 5% for the case of "discounting of benefits".
i = 0% for the case of "no discounting of benefits".

Inflation f = 5%

N = 30 years

VT (in constant $ of 1989) = $5/h
VAC (in constant $ of 1989) = $5000 for property damage/accident*
+ $5000 (for injury, fatality)/accident*
= $10,000/accident

---

* In 1987, Ontario:
21,235 accidents were reported for "Other King's" Highways
402 fatalities were reported for these highways
14,735 persons were injured on these highways
$5000/accident (average) for property damage
1 fatality for 52.82 accidents
1 injury for 1.44 accidents.

Estimation of Benefits (Overtaking Allowed)

DHV	300	500	1000	1500
Without Discounting of Benefits				
Delay Reduction (hrs/yr)	533	1369	2739	5280
Benefits Due to Delay Reduction/Yr (1989$)	2665	6848	13695	26440
Reduction in Accidents/Yr	1.7	4.4	7.7	13.4
Benefits Due to Accident Reduction/Yr (1989$)	17000	44000	77000	134000
Benefits Due to Accident Reduction (Property Damage Only) (1989$)	8500	22000	38500	67000
With Discounting of Benefits				
Benefits Due to Delay Reduction/Yr 1989$)	1366	3509	7016	13549
Benefits Due to Accident Reduction/Yr (1989$)	8711	22546	39456	68664
Benefits Due to Accident Reduction (Property Damage Only) (1989$)	4356	11273	19728	34332

Cost of Climbing Lane/km (1989$) = $396,000/km

Maintenance Cost/km (1989$) = Assumed to be zero in this example

Total Cost/km = $396,000/km

Cost of Climbing Lane (1989$)/Yr = (2 km x $396,000)/30 yrs
= $26,400/yr

Net Benefits				
DHV	300	500	1000	1500
AADT	1724	2874	5747	8621
Without Discounting of Benefits				
Delay Reduction/ Yr (1989$)	2665	6848	13695	26440
Safety Benefits/ Yr (1989$)	17000	44000	77000	134000
Total Benefits/ Yr (1989$)	19665	50848	90695	160440
Cost/Yr (1989$)	26400	26400	26400	26400
Net Benefits/Yr (1989$)	-6735	24448	64295	134040
With Discounting of Benefits				
Delay Reduction/ Yr (1989$)	1366	3509	7016	13549
Safety Benefits/ Yr (1989$)	8711	22546	39456	68664
Total Benefits/Yr (1989$)	10077	26055	46472	82213
Cost/Yr (1989$)	26400	26400	26400	26400
Net Benefits/Yr (1989$)	-16323	-345	20072	55813

A graphical presentation of results is shown in Figure 8.2. It can be noted from the above tabulated results as well as the diagram that a climbing lane is feasible for a DHV of 500. The truck speed criterion is also positive. However, according to the level of service warrants/guidelines, a climbing lane would not be warranted at this level of traffic. The economic feasibility criterion has a more profound base than the LOS criterion for the provision of a climbing lane. Therefore, it would be logical to give a higher weight to the results of cost-effectiveness evaluation in decision-making.

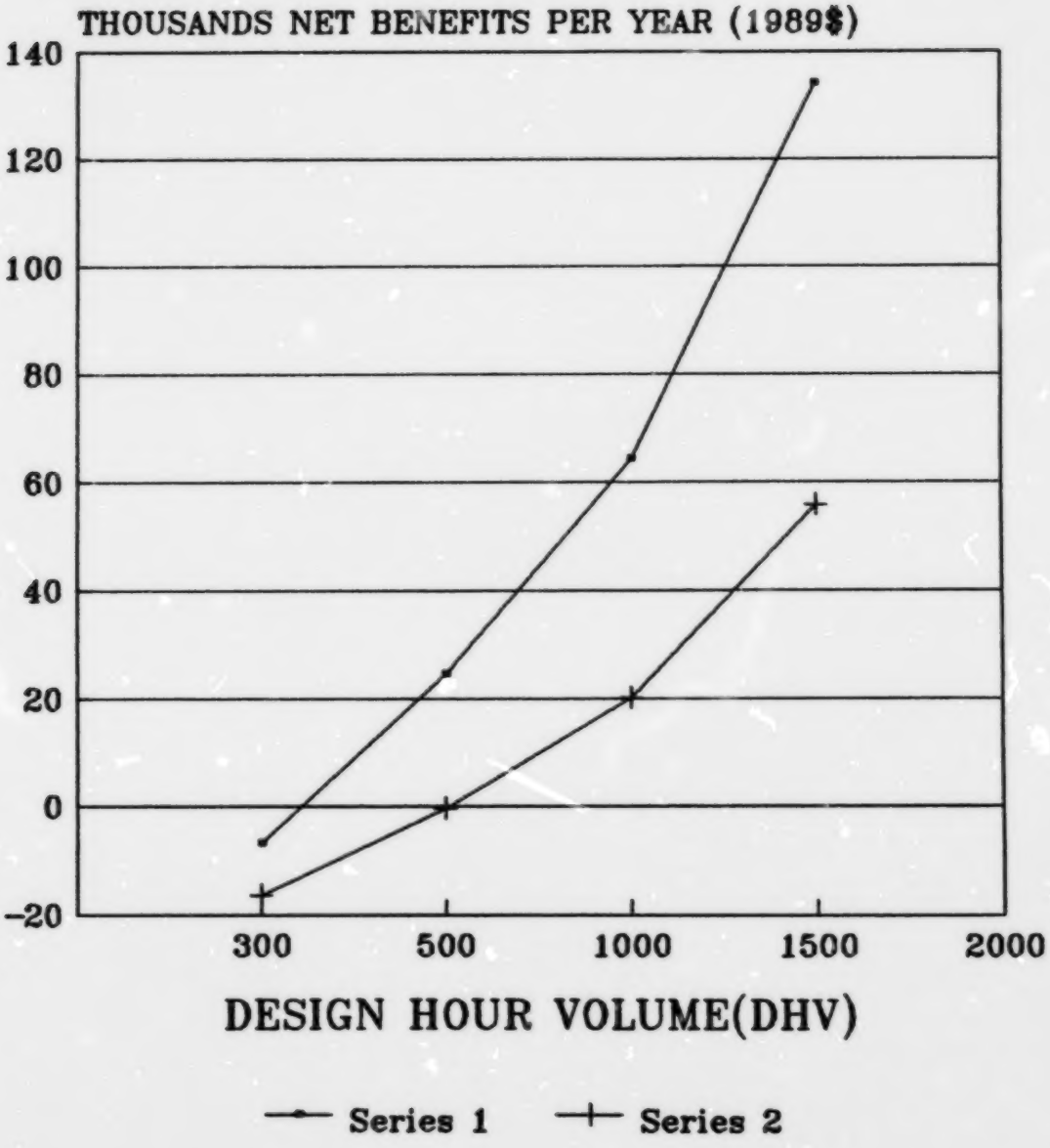


Figure 8.2: Economic Feasibility of Climbing Lane

Cost-Effectiveness				
DHV	300	500	1000	1500
AADT	1724	2874	5747	8621
Cost/ 100 Vehicles per Yr (1989$)	8.40	5.04	2.52	1.68
Cost/ 100 Veh-km (1989$)	1.91	1.15	0.57	0.38
Effectiveness: Single Measures				
Delay Reduction (hrs/yr)	533	1369	2739	5280
Delay Reduction (min/100 vehicles)	5.1	7.9	7.9	10.1
Veh-hrs of Delay Reduction/$ of Cost	0.02	0.05	0.11	0.20
$ of Cost/Veh-hr of Delay Reduction	49.53	19.28	9.63	5.00
Accident Reduction/Yr	1.7	4.4	7.7	13.4
Accident Reduction/ Million Veh-km	1.23	1.90	1.67	1.94
Accident Reduction/ $m of Cost	64.39	166.67	291.67	507.58
$ of Cost/Accident Reduction	15529	6000	3429	1970
Overall Effectiveness (Relative Value Scale)				
Index of Overall Effectiveness	0.12	0.30	0.55	1.00

Selected results of cost-effectiveness evaluation are plotted in Figures 8.3 to 8.5. Results clearly show that the cost-effectiveness of the climbing lane improves with increasing DHV.

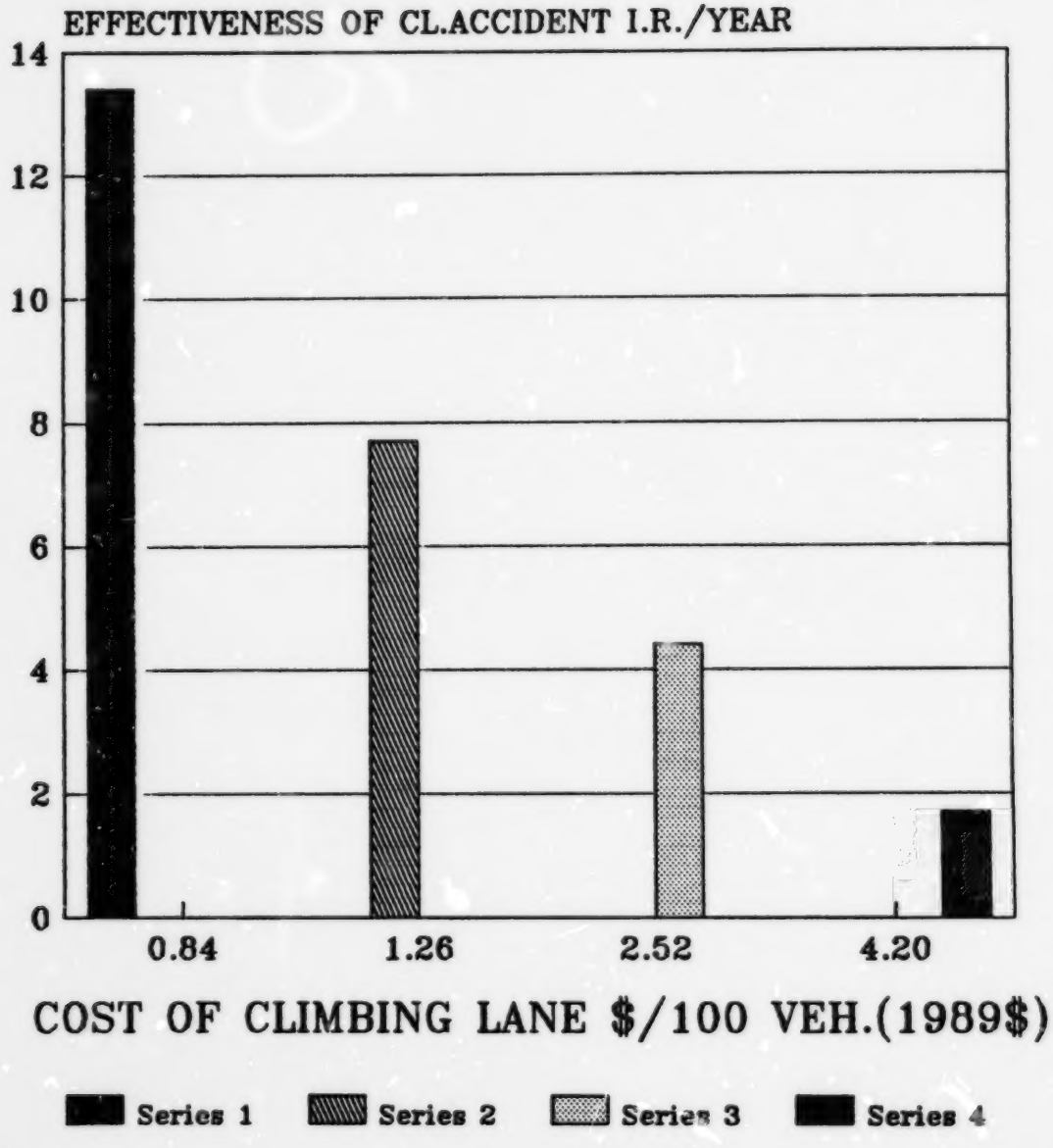


Figure 8.3: Cost-Effectiveness of Climbing Lane: Safety

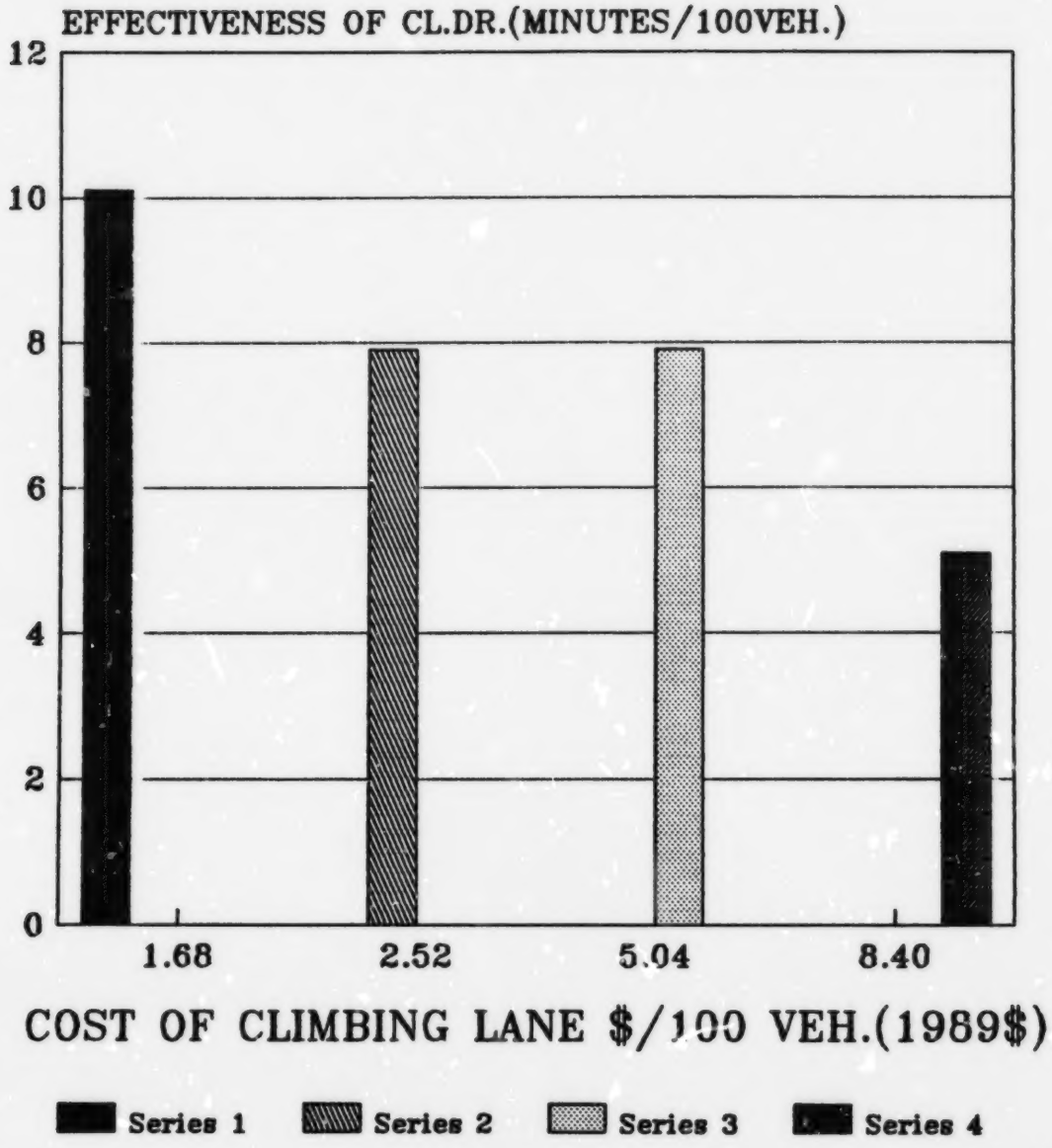


Figure 8.4: Cost-Effectiveness of Climbing Lane: Delay Reduction

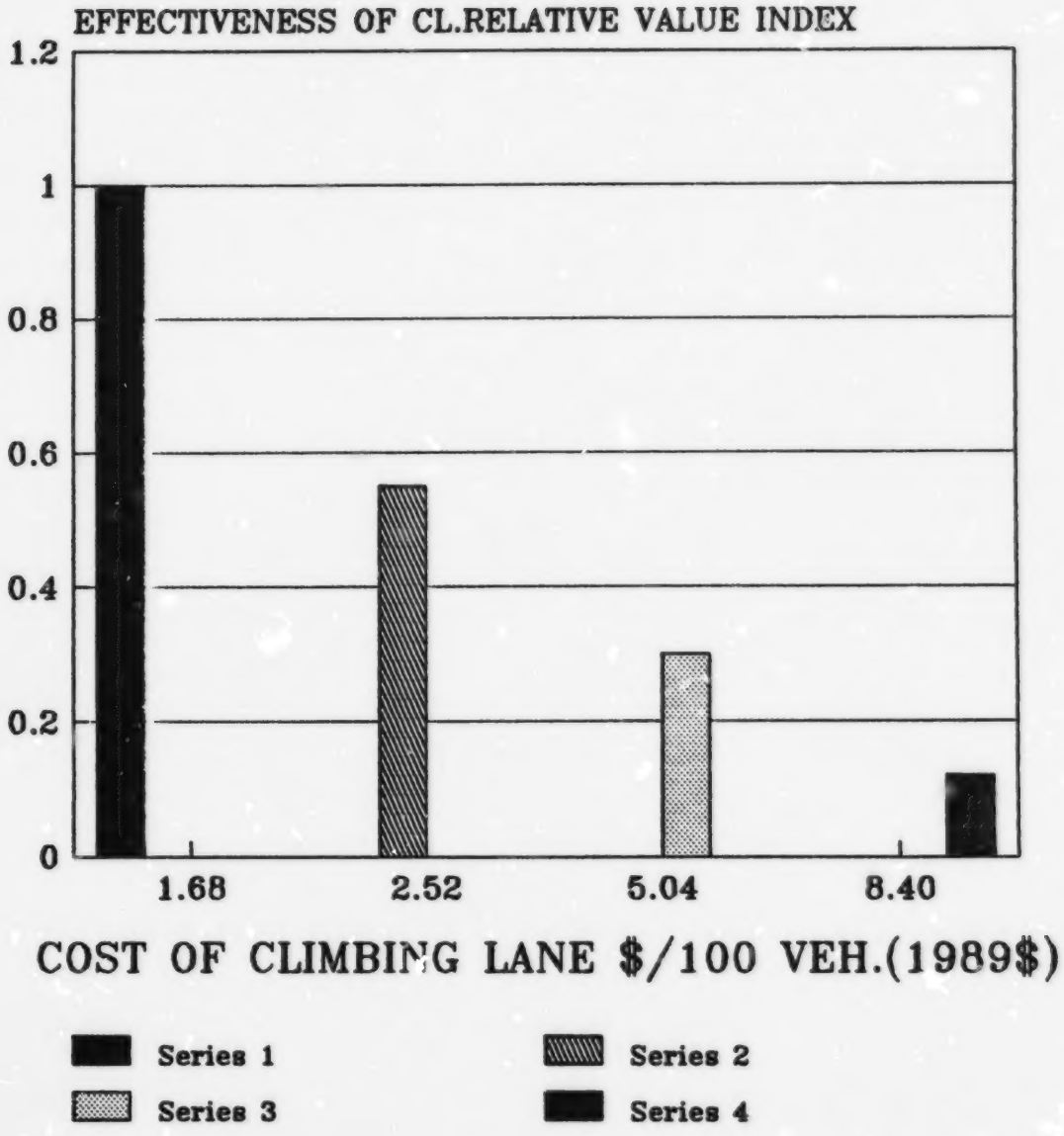


Figure 8.5: Cost-Effectiveness of Climbing Lane: Combined Effectiveness Index

Outputs of the CECL Program, covering effectiveness measures, economic feasibility, and cost-effectiveness type of evaluations (Modules D to G) are shown in Table 8.6.

The CECL Program was used to illustrate a sensitivity analysis. The effect of grade on the satisfaction of warrants and the cost-effectiveness of the climbing example was studied. The results are summarized in Table 8.7.

Table 8.6

Economic Feasibility and Cost-Effectiveness Evaluation Outputs

```
                    ECL 1.12 - Effectiveness Measures
                                          Thu Aug 16 12:23:08 1990
Site: test01    Example from report

     WEIGHTS
       Delay Reduction:      0.40
       Accident Reduction:   0.60

     COST DATA
       Base Year:  1989
       Real Rate of Return:    5.00 %

       Facility Life:          30 yr
       Vehicle Hour Cost:      5.00 $
       Vehicle Acc. Cost:     10000 $
       Lane Unit Cost:       396000 $/km
       Lane Fixed Cost:           0 $
       Maintenance Cost:          0 $/km/yr

  SINGLE EFFECTIVENESS MEASURES:
     DHV                300      500     1000     1500  veh/hr
     AADT              1724     2874     5747     8621  veh/day
     Delay Red.         5.1      7.6      7.8     10.0  min/100 veh

Alt-H=Help.  F1=Explain.  Alt-F1=Keys.  Ctrl-F1=About EffMeas        F10=Menu
```

Table 8.6 (Cont.)

Economic Feasibility and Cost-Effectiveness Evaluation Outputs

CECL 1.12 - Effectiveness Measures

Delay Red.	5.1	7.6	7.8	10.0	min/100 veh
Acc. Red.	1.26	1.84	1.66	1.92	acc/M veh-km

MULTIPLE EFFECTIVENESS MEASURES:

DHV	300	500	1000	1500	veh/hr
Delay Red.	0.101	0.255	0.520	1.000	relative
Acc. Red.	0.130	0.318	0.576	1.000	relative
Weighted Eff.	0.119	0.293	0.554	1.000	

COSTS OF ADDING CLIMBING LANE:

Lane Length = 2.00 km Roadway Length = 2.20 km
Lane Construction Cost = 396000 $/km
Lane Maintenance Cost = 0 $/km/yr

Total Lane Construction Cost =	792000 $ =	26400	$/yr
Total Lane Maintenance Cost	=	0	$/yr
TOTAL LANE COST	=	26400	$/yr

BENEFITS FROM ADDING CLIMBING LANE:

Alt-H=Help. F1=Explain. Alt-F1=Keys. Ctrl-F1=About EffMeas F10=Menu

Table 8.6 (Cont.)

Economic Feasibility and Cost-Effectiveness Evaluation Outputs

ECL 1.12 - Effectiveness Measures

BENEFITS FROM ADDING CLIMBING LANE:					
DHV	300	500	1000	1500	veh/yr
Delay Red.	530.7	1335.4	2728.2	5245.9	hr/yr
Acc. Red.	1.74	4.24	7.67	13.32	acc/yr
Without discounting of benefits:					
DR Benefits	2653	6677	13641	26229	1989$/yr
AR Benefits	17380	42360	76730	133200	1989$/yr
Total Benefits	20033	49037	90371	159429	1989$/yr
Net Benefits	-6367	22637	63971	133029	1989$/yr
With discounting of benefits using a 5.00% rate of return:					
DR Benefits	1360	3421	6990	13440	1989$/yr
AR Benefits	8906	21706	39318	68254	1989$/yr
Total Benefits	10265	25127	46307	81694	1989$/yr
Net Benefits	-16135	-1273	19907	55294	1989$/yr
COST-EFFECTIVENESS VALUES:					
DHV	300	500	1000	1500	veh/hr
AADT	1724	2874	5747	8621	veh/day
Annual Cost	26400	26400	26400	26400	1989$/yr

Alt-H=Help. F1=Explain. Alt-F1=Keys. Ctrl-F1=About EffMeas F10=Menu

Table 8.6 (Cont.)

Economic Feasibility and Cost-Effectiveness Evaluation Outputs

ECL 1.12 - Effectiveness Measures

Annual Cost	26400	26400	26400	26400	1989$/yr
Cost	4.20	2.52	1.26	0.84	1989$/100 veh
Cost	1.91	1.14	0.57	0.38	1989$/100 veh-km
Effectiveness: Single Measures					
Delay Red.	531	1335	2728	5246	hr/yr
Delay Red.	5.06	7.64	7.80	10.00	min/100 veh
hr/$	0.02	0.05	0.10	0.20	veh-hr/1989$
$/hr	49.75	19.77	9.68	5.03	1989$/veh-hr
Acc. Red.	1.7	4.2	7.7	13.3	acc/yr
Acc. Red.	1.26	1.84	1.66	1.92	acc/M veh-km
acc red/$M	65.83	160.45	290.64	504.55	acc red/M1989$
$cost/acc red	15190	6232	3441	1982	1989$/acc red
Weighted Eff.	0.119	0.293	0.554	1.000	

Alt-H-Help. F1-Explain. Alt-F1-Keys. Ctrl-F1-About E1fMeas F10-Menu

Table 8.7

Sensitivity Analysis of Climbing Lane Decision Problem:
Results of CECL Program

DHV (veh/h)	300	500	1000	1500
Approach Section				
Approach Speed (km/h)	93.4	91.3	83.7	80.3
Approach LOS	A	A	B	B
3% Grade				
Truck Speed Drop Warrant	Yes	Yes	Yes	Yes
LOS (No Cl. Lane)	A	B	B	C
LOS Warrant	No	No	No	Yes
Net Benefits/Yr (1989$)	-26,400	-26,400	-26,400	-17,015
$ of Cost/ Accident Reduced	NA	NA	NA	16,977
4% Grade				
Truck Speed Drop Warrant	Yes	Yes	Yes	Yes
LOS (No Cl. Lane)	A	B	B	C
LOS Warrant	No	No	No	Yes
Net Benefits/Yr (1989$)	-26,400	-25,351	-20,013	-4,866
$ of Cost/ Accident Reduced	NA	147,486	24,650	7,418
5% Grade				
Truck Speed Drop Warrant	Yes	Yes	Yes	Yes
LOS (No Cl. Lane)	B	B	B	C
LOS Warrant	No	No	No	Yes
Net Benefits/Yr (1989$)	-26,400	-19,791	-10,235	9,212
$ of Cost/ Accident Reduced	NA	23,476	9,767	4,479

For 6% and 7% grades, please see next page.

Table 8.7 (Continued)

Sensitivity Analysis of Climbing Lane Decision Problem: Results of CECL Program

DHV (veh/h)	300	500	1000	1500
Approach Section				
Approach Speed (km/h)	93.4	91.3	83.7	80.3
Approach LOS	A	A	B	B
6% Grade				
Truck Speed Drop Warrant	Yes	Yes	Yes	Yes
LOS (No Cl. Lane)	B	B	C	C
LOS Warrant	No	No	Yes	Yes
Net Benefits/Yr (1989$)	-22,846	-11,230	4,236	31,277
$ of Cost/ Accident Reduced	43,636	10,268	5,175	2,792
7% Grade				
Truck Speed Drop Warrant	Yes	Yes	Yes	Yes
LOS (No Cl. Lane)	B	B	C	C
LOS Warrant	No	No	Yes	Yes
Net Benefits/Yr (1989$)	-16,135	-1,273	19,907	55,294
$ of Cost/ Accident Reduced	15,190	6,232	3,441	1,982

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The following conclusions can be drawn from the research conducted and findings reported here.

1. The Highway Capacity Manual (1985) or any other design manual currently in use do not offer guidelines or methodology for the analysis of level of service of two lane highway sections with auxiliary lanes. Specifically, prior to this study, a formal methodology for estimating the performance of upgrade sections of two lane highways with climbing lanes was not available. The microscopic simulation programs (e.g., TWOPAS, TRARR) are not readily available to designers and may not be regarded as "practical" for the assessment of climbing lane options.

2. The procedures and LOS criteria contained in the HCM (1985) for the level sections result in inconsistent answers when compared to results obtained from those used for upgrade sections (without climbing lanes). For a given traffic level, a higher level of service could be indicated for upgrade section (with a lower average operating speed) as opposed to the approach section on level grade and a higher average speed. In some instances, the use of level grade procedures may result in a lower average speed as compared to upgrade speed. Also, given otherwise identical traffic and highway conditions, the use of HCM (1985) without adjustment may show a better level of service on a specific grade than on level or rolling terrain. It appears that the procedures for analyzing level sections and those for upgrade sections contained in the HCM (1985) have not been harmonized. Yet, for the analysis of two lane sections with specific grades, such a comparison is required for realistic calculations of delay to vehicles on the upgrade section. The methodology developed in this research attempts to overcome this deficiency.

3. The development of methodology for the analysis of upgrade sections with climbing lanes involved the study of traffic platooning measures (e.g., percent time delay, percent following) and traffic speed measures. For ease of measurement and consistency of with Chapter 8 of the HCM (1985), the level of service criteria for upgrade sections were related to the average speed.

4. The approach used in this study for the development of models that enable the estimation of operational effectiveness of upgrade sections of two lane roads, has proven to be the most appropriate for the task at hand. The information obtained from the microscopic simulation of highway sections and using the output in conjunction with geometric and traffic characteristics for the calibration of regression models of average speed is an inexpensive and reliable and effective approach. The regression equations provide realistic estimates of the performance of highway section, with and without climbing lanes.

5. A comparison of two microsimulation models, namely the TWOPAS and TRARR suggests that these models have generally similar capabilities and their results are were comparable. However, the TWOPAS simulator was selected for use in this study for its outputs and experience with its applications.

6. Results obtained from the TWOPAS and regression models check favourably with each other as well as with field survey data collected from sites with and without climbing lanes. The TWOPAS model is useful for a very detailed microsimulation of upgrade sections on two lane highways. On the other hand, the regression models are very satisfactory for macrosimulation of such sites.

7. The regression models provide a realistic basis for the operational analysis of upgrade sections containing lanes. Prior to this study, such a methodology was not available.

8. Accident involvement rates rise with increasing differences in the operating speeds of adjacent sections of a two lane highway. Available information suggests that climbing lanes are effective in reducing accidents on upgrade sections of two lane highways owing to increased opportunities to pass slow vehicles, reduction in platoons and enhanced operating speeds.

9. The determinants of the effectiveness of a climbing lane are: gradient, length of grade, traffic volume, percent trucks, percent recreational vehicles, directional distribution of traffic, and the presence/absence of "no passing zones". All the roadway and traffic features that contribute to the formation of platoons are incorporated in regression equations for the estimation of upgrade average speed.

10. Application of the methodology developed in this study suggests that climbing lanes are effective in improving the determinants of level of service on two lane highways. The simulations that were used as a basis for development of regression equations suggests that climbing lanes reduce percent time delay, increase average speed, reduce traffic

platoons. The higher spot speeds at the end of climbing lanes are an indication of traffic operational benefits on two-lane highways downstream. For most traffic levels tested, climbing lanes ending beyond crest give somewhat higher average speed upgrade than the case where climbing lane ends at crest.

11. The methodology for the study of cost-effectiveness is useful for assessing climbing lane alternatives. Also, the methodology incorporates the opportunity to test the economic viability of climbing lane options.

12. On the basis of a test case examined, climbing lanes, despite their substantial capital cost, appear to be cost-effective and economically feasible, for higher grades and higher traffic volume levels.

13. The microcomputer program, incorporating the overall methodology, is an effective user friendly tool. It enables an expedient and comprehensive assessment of climbing lane projects.

9.2 Recommendations

1. The methodology developed for estimating the length of climbing lanes, their operational and safety analysis, and their cost-effectiveness evaluations should be adopted by the Ministry of Transportation, Ontario.

2. Given the generally similar function of climbing and passing lanes, the methodological approach used in this study should be extended to include passing lanes.

3. New research should aim the development of techniques that look at both climbing and passing lanes as options for the improvement of safety and operations of two lane highways. Such a methodology would enable priority analysis of passing/climbing lane solutions on two lane rural roads.

REFERENCES

1. Khan, A.M., et. al., "Heavy Vehicle Performance on Grade and Climbing Lane Criteria", Prepared for Research & Development Branch, Ministry of Transportation, Ontario, Transportation Research Centre, Carleton University, March 1989.

2. Transportation Research Board, "Highway Capacity Manual", Special Report 209, Washington, D.C., 1985.
Much of the research information used for the rural highway chapter is contained in Messer, C.J., "Two-Lane, Two-Way Rural Highway Capacity", Final Report, NCHRP Project 3-28A, Texas Transportation Institute, College Station, Tx., Feb. 1985 .

3. American Association of State Highway and Transportation Officials, "Geometric design of Highways and Streets", washington, D.C., 1984.

4. Polous, A. et. al., "Applying the Level of Service Concept to Climbing Lanes", Transportation Research Record 806.

5. Ministry of Transportation, Ontario, "Geometric Design Standards for Ontario Highways", Highway Design Office, 1985, Queen's Printers.

6. Ministry of Transportation, Ontario, "Minutes of Executive Meeting, WP 905-76-01-Auxiliary Lane Analysis", June 5, 1986.

7. Homburger, W.S., "An Analysis of Safety at Upgrade Terminals of Climbing lanes on TWO-Lane Highways", Transportation Research Record 1122, 1987.

8. Hoban, C.J. and J.F. Morral, "Overtaking Lane Practice in Canada and Australia", Internal Report AIR 359-15, Australian Road Research Board, June 1985.

9. Hoban, C.J., "Traffic Performance on Transition Between Two-Lane Rural Roads and Four Lane Cross Sections", Proceedings of 10th Australian Road Research Board Conference, 1986.

10. Glennon, J.C., "An Evaluation of Design Criteria for Operating Trucks Safely on Grades", Highway Research Record 312, 1970.

11. Harwood, D.W. and C.J. Hoban, "Low Cost Methods for Improving Traffic Operations on Two lane Roads: Information Guide", FHWA/IP-87/2, Jan. 1987.

12. Harwood, D.W. and A.D. St. John, "Operational Effectiveness of Passing Lanes on Two Lane Highways", FHWA/RD-86/195, June 1986.

13. Morral, J.F. and A. Werner, "Measuring Two-Lane Highway Level of service by Overtaking " Transportation Research Board, 1990.

14. Federal Highway Administration, " TWOPAS User's Guide", A User's Guide to TWOPAS - A Microscopic Computer Simulation Model of Traffic on Two-Lane, Two-Way Highways", U.S. Department of Transportation, May 1986.

15. Hoban, C.J., G.J. Fawcett and G.K. Robinson, "A Model for Simulating Traffic on Two-Lane Rural Roads: User Guide and Manual for TRARR Version 3.0", Australian Road Research Board, ATM10A, May 1985. Australian Road Research Board, "TRARR 3.1 - Rural Traffic Simulation Model, Notes on Version 3.1".

16. ADI, "Evaluation of Passing Lane Safety", Prepared for Transport Canada, September 1988.

17. Hoban, C., " Low Cost Methods for Improving Traffic Operations and Safety on Rural Roads", Australian Road Research Report (Draft), 1987.

18. Jorgensen, R.E., "Evaluation of Criteria for Safety Improvements on Highways", U.S. Department of Commerce, BPR, Washington, D.C., 1966.

19. Martin and Voorhees Associates, "Crawler Lanes Study: An Economic Evaluation", Dept. of Environment., London, 1978.

20. Rinde, E.A., "Accident Rates vs. Shoulder Widths", California Dept. of Transportation, Sacramento, 1977.

21. Harwood, D.W., A.D. St. John and D.L. Warren, "Operational and Safety Effectiveness of Passing Lanes on Two-Way Highways", Transportation Research Board 64th Annual Meeting, 1985.

22. Ministry of Transportation, Ontario, "Provincial Highways, Trends Overview", 1988.

23. Federal Highways Administration, "Guide for Monitoring and Enhancing Safety on the National Truck Network", Office of Highway Safety, 1986.

24. Polus, a. and I. Reshetnik, "Impact of Passing-Climbing Lanes on Traffic Flow on Upgrades", Transportation Research A, V. 21A, No. 6, 1987.

25. Botha, J.L., et.al., "A Decision-Making Framework for the Evaluation of Climbing Lanes on Two-Lane Two-Way Rural Roads: Research Summary", Institute of Transportation Studies, University of California, Berkeley, CA., 1980.

26. Robinson, G.K., "Use of A Traffic Simulation Model to Formulate A Climbing Lane Warrant", Australian Road Research Board, Internal Report, AIR 290-1, 1980.

27. Guell, D.L., and M.R. Virkler, "Capacity Analysis of Two-Lane Highways", Transportation Research Board Annual Meeting, 1988.